



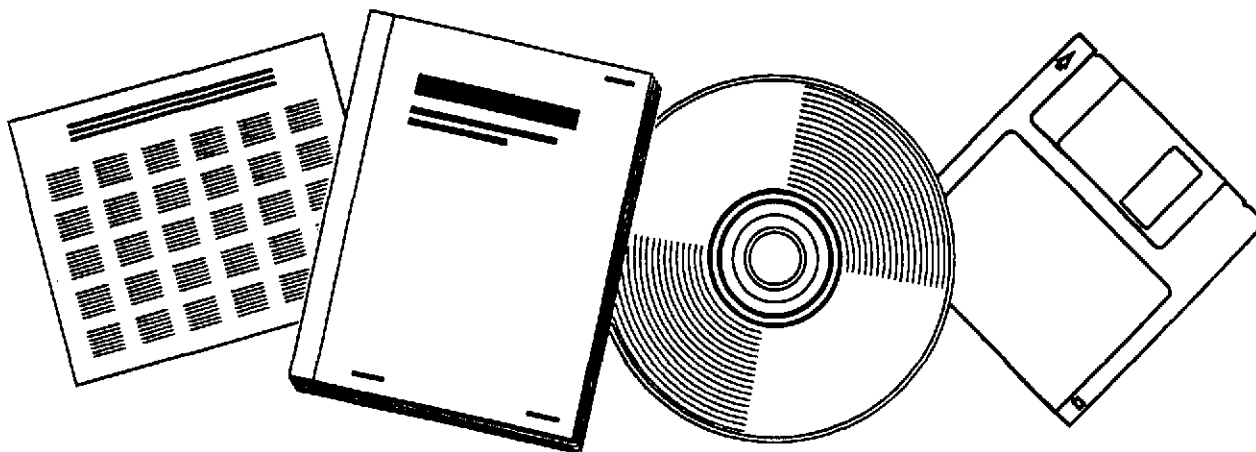
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DICHOTOMOUS SAMPLER FOR TRIG AEROSOL AND VAPOR, FINAL PERFORMANCE REPORT FEBRUARY 1, 1992-JANUARY 31, 1995

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A Dichotomous Sampler for TRIG Aerosol and Vapor
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Principal Investigator: Roy J. Rando, Sc.D., C.I.H.
Associate Professor of Environmental Health Sciences

Participating Investigators: John J. Lefante, Ph.D.
Associate Professor of Biostatistics

Halet G. Poovey, M.S.P.H., C.I.H.
Associate Scientist

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16. Abstract (Limit: 200 words) An analytical technique was developed to reliably measure total reactive isocyanate group (TRIG) in workplace atmosphere samples and the technique was adapted for use in a dichotomous sampler that would separately collect and measure TRIG in the vapor and condensed phases. Three candidate derivatizing agents for TRIG measurement were evaluated: methoxy-phenylpiperazine (MOPIP), 9-methylamino-methylanthracene (MAMA), and tryptamine (TRYP). Six commercial formulations of isocyanate oligomers/polyurethane prepolymers were assayed by derivation with MAMA followed by high performance liquid chromatography with ultraviolet absorbance and fluorescence detection. A dichotomous sampler consisting of an impactor inlet in series with two sections of annular denuder tube followed by a backup filter was used to study the partitioning of 4,4'-diphenylmethane-diisocyanate (101688) between the vapor phase and condensed phase in an atmosphere of condensation aerosol ranging from 24 to 335 micrograms/cubic meter. Test atmospheres of HDI vapor and of 1,6-hexamethylenediisocyanate(822060)/1,6-hexamethylenediisocyanate-biuret(4035896)aerosols were generated and sampled with the dichotomous sampler using MAMA reagent. The dichotomous sampler was used to measure vapor and condensed phase TRIG in workplace atmospheres.			
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List of Abbreviations

AED:	Aerodynamic Equivalent Diameter
ANOVA:	Analysis of Variance
BEN:	Benzylisocyanate
BUT:	Butylisocyanate
CMDI:	Poly-methylene-poly-phenyleneisocyanate
CV:	Coefficient of Variation
D₅₀:	Cut Diameter; 50% Efficiency
DMSO:	Dimethylsulfoxide
HDI:	1,6-Diisocyanatohexane, 1,6-hexamethylenediisocyanate
HEPA:	High Efficiency Particulate
HMDI:	Methylene-bis-(4,4'-cyclohexylisocyanate)
HPLC:	High Performance Liquid Chromatography
HSE:	Health and Safety Executive
HVAC:	Heating, Ventilation, and Air Conditioning
M20S:	Lupranate M20S
MAMA:	9-Methylamino-methylantracene
MDI:	4,4'-Diphenylmethane-diisocyanate
MIC:	Methylisocyanate
mM NCO:	Millimoles of Isocyanate Equivalence per Liter
MOPIP:	Methoxy-phenylpiperazine
NCO:	Isocyanate Functional Group
ND:	Not Detected
NIOSH:	National Institute for Occupational Safety and Health
OSHA:	Occupational Safety and Health Administration
OTOL:	o-Tolylisocyanate
PEL:	Permissible Exposure Limit
PIC:	Phenylisocyanate
PMPPi:	Polymethylene-polyphenyl-isocyanate
PPB:	Parts per Billion
PTOL:	p-Tolylisocyanate
RF:	Response Factor
RSD:	Relative Standard Deviation
STEL:	Short Term Exposure Limit
TBP:	Tributylphosphate
TDI :	Toluenediisocyanate (2,4-TDI), (2,6-TDI)
TRIG:	Total Reactive Isocyanate Group
TRYP:	Tryptamine
UV:	Ultraviolet
VOA:	Volatile Organic Analysis

1.) Significant Findings

- *Selection of Derivatizing Agent for Measurement of TRIG* Three candidate derivatizing agents for measurement of TRIG were evaluated: methoxy-phenylpiperazine (MOPIP), 9-methylamino-methylanthracene (MAMA), and tryptamine (TRYP). Derivatives of eleven isocyanate monomers with each of the three derivatizing agents were synthesized in the laboratory. The response factors for each of these derivatives were measured for three separate analytical techniques applicable to detection/quantitation with liquid chromatography. MOPIP derivatives were measured by UV absorbance at 242 nm and 277 nm and by electrochemical detection. MAMA derivatives were measured by UV absorbance at 245 nm and at 370 nm and by fluorescence. TRYP derivatives were measured by UV absorbance at 280 nm, electrochemical detection and fluorescence. In comparing consistency of response factors across the eleven isocyanates, MAMA derivatization exhibited the least variability, with relative standard deviations of 14%, 8.6%, and 55% for UV absorbance at 245 nm, UV absorbance at 370 nm, and fluorescence, respectively. The ratio of response factors for UV absorbance at 245 nm to that at 370 nm had a mean value of 10.5 and an RSD of 8.3%. These results indicated that MAMA derivatization provided the most reliable means of identifying unknown isocyanates in environmental samples
- *Measurement of TRIG in Oligomeric and Pre-polymeric Isocyanates* Six commercial formulations of isocyanate oligomers/polyurethane pre-polymers were assayed by derivatization with MAMA followed by HPLC analysis with detection by UV absorbance and fluorescence. Three of the commercial formulations were based on MDI, and contained MDI monomer as well as oligomers of MDI. Two of the samples were based on HDI, one being an oligomeric mixture containing primarily HDI-biuret, and the second being the isocyanate component of a two-part polyurethane paint, also containing primarily HDI-biuret. The final sample was a commercial, heavy-duty, moisture-curing polyurethane varnish, containing a polyol modified with TDI and free 2,4-TDI and 2,6-TDI. In each sample, the parent isocyanate monomer was identified. Using the ratio of UV absorbance at 245 nm to 370 nm as the selection criteria, at least one and up to four other compounds were identified in the samples as having contained free isocyanate group. Quantitation of TRIG in these samples was done using standards prepared from the parent isocyanate monomer. In comparison to a reference titration assay, analytical recoveries of TRIG for the MAMA technique ranged from 95% to 107%.
- *Partitioning of MDI between Vapor and Condensation Aerosol* A dichotomous sampler consisting of an impactor inlet in series with two sections of annular denuder tube followed by a backup filter was used to study the partitioning of MDI between the vapor phase and condensed phase in an atmosphere of condensation aerosol ranging from $24 \mu\text{g}/\text{m}^3$ to $355 \mu\text{g}/\text{m}^3$. The walls of the denuder tubes and the backup filter were coated with N-4-nitrobenzyl-N-n-propylamine for derivatization of MDI followed by HPLC analysis. Efficient collection of MDI vapor was accomplished by the diffusional denuders, while MDI condensation aerosol passed through the denuders to be collected by the backup filter. The dichotomous sampler indicated that MDI was found only in the vapor phase below about $75 \mu\text{g}/\text{m}^3$; above this value, increasingly larger amounts of MDI were found on the backup filter as overall concentration increased. However, the amount collected by the denuders became essentially constant. These results were in concordance with the

saturated vapor pressure of MDI which has been reported to be between 55 $\mu\text{g}/\text{m}^3$ and 100 $\mu\text{g}/\text{m}^3$ at temperatures of 25 to 27 °C.

- Partitioning of HDI between Vapor and HDI-biuret Aerosols Test atmospheres of HDI vapor and of HDI/HDI-biuret aerosols were generated in the laboratory and sampled with the dichotomous sampler using MAMA reagent. For sampling of test atmospheres of HDI vapor, HDI was completely collected by the diffusional denuders, indicating complete separation of HDI into the vapor phase. When a mixture of HDI-biuret and HDI was nebulized, the dichotomous sampler indicated that approximately 78% of the HDI was in the vapor phase, whereas about 22% was associated with the aerosol fraction. In these tests, the HDI concentration was 30 ppb on average. This was about three orders of magnitude less than the saturated vapor pressure concentration of HDI. Thus significant partitioning of HDI between vapor and condensed phases was demonstrated, even when well below the vapor saturation point.
- Characterization of TRIG in Workplace Atmospheres The dichotomous sampler was used to measure vapor and condensed phase TRIG in representative workplace atmospheres. The first field test was conducted in a paint spray booth during application of a polyurethane paint. Up to 554 $\mu\text{g}/\text{m}^3$ of TRIG was measured in the spray paint booth atmosphere during the painting operation. Most of the TRIG was HDI-biuret which was only found in the aerosol fraction of the atmosphere. Small amounts of HDI monomer were measured as well. During the painting operation, about 20 to 30% of the HDI was present in the aerosol fraction. After spraying was finished, small amounts of HDI were measured from offgassing of the newly painted surfaces. However, in this case all of the HDI was present in the vapor phase.

Sampling was also conducted in a factory producing flexible polyurethane foam products. Both TDI and MDI were used in the polyurethane foam formulations. While no MDI was detected in any of the samples taken in the foam factory, levels of TDI up to about 18 ppb were measured along the foam lines. The majority of the TDI was found in the vapor phase. In addition to TDI, small amounts of other TRIG compounds were measured in the atmosphere as well. These compounds were always associated with the presence of TDI but were usually less than half its concentration. As in the case of TDI, these compounds were also mostly present in the vapor phase, indicating that they were probably of low molecular weight and not polymeric in nature. Measurement of low levels of TDI and TRIG near foam finishing processes which utilize high temperatures or pyrolysis, supported the contention that isocyanates may be released from fully cured polyurethanes by thermal degradation and chemical rearrangement.

2.) Usefulness of Findings

The isocyanates are an important group of industrial chemicals used in formulating polyurethane foams, plastics, and paints. Certain isocyanate compounds such as TDI, MDI and HDI are known to cause occupational asthma and other respiratory diseases. Legal standards and exposure guidelines exist for these widely used industrial chemicals. There is increasing concern that other isocyanate compounds formed during the chemical reactions occurring when polyurethanes are manufactured or are degraded by hot processes may also

be capable of causing occupational diseases. No exposure guidelines for these non-traditional isocyanate compounds exist in the US, although the United Kingdom has developed an exposure standard for total reactive isocyanate group (TRIG). In order to evaluate exposures to these materials, reliable techniques for their collection and measurement in the workplace are needed. This project has demonstrated a new analytical approach to the measurement of TRIG which allows its identification and quantitation even when its exact chemical identity is uncertain. This new technique was shown to be superior to other currently used methods in terms of specificity, accuracy, ease of use, and reliability. The technique was also adapted to a new sampling device which enables separate measurement of TRIG in the vapor phase and in the airborne particle phase. Knowledge of how TRIG partitions between vapor and particulate phases is important in understanding where the material deposits in the body when it is inhaled, and is also useful in designing appropriate control technologies, such as air filtration systems, for minimization of worker exposure. Project studies conducted in the laboratory and in actual workplaces demonstrated the presence of TRIG arising from the commercial isocyanates as well as from their chemical reaction products and indicated that partitioning of these materials between vapor and particulate phases is a significant phenomenon. The results of this project point out the need for further research on the identity and behavior of TRIG in workplace atmospheres. Also, with this new technique for measurement of TRIG, it should now be possible for the first time to conduct epidemiologic assessments of working populations which are exposed, in an effort to identify and quantify the risks associated with occupational exposure to these materials.

3.) Abstract

The objectives of this project were to develop an analytical technique capable of reliably measuring TRIG in workplace atmosphere samples and adapting the technique to use in a dichotomous sampler that would separately collect and measure TRIG in the vapor and condensed phases. Three derivatizing agents for TRIG (MOPIP, MAMA, and TRYP) were evaluated by preparing their respective urea derivatives with eleven different isocyanate monomers representing aliphatic, aromatic, mono- and di-isocyanates. The analytical response of each of the derivatives was measured using three independent detection methods, either UV absorbance at a single or multiple wavelengths, electrochemical detection, or fluorescence. Using the criteria of consistency of analytical response across the isocyanates, MAMA reagent exhibited the best performance among the three candidate agents. The ratio of UV absorbance at 245 nm and at 370 nm for the eleven isocyanate-MAMA derivatives had a mean value of 10.5 with a relative standard deviation of only 8.3%. These derivatives were also highly fluorescent which could be used as a secondary confirmation of their identity. The MAMA technique was applied to the determination of TRIG in six different commercial formulations, four of which were industrial products containing monomers and oligomers of HDI or MDI, and the other two being commercial polyurethane paints/coatings, one based on HDI and the other, TDI. Using the ratio of UV absorbance at the two critical wavelengths after MAMA derivatization and HPLC analysis, the parent isocyanate monomer was identified in these materials, as well as a multitude of other isocyanate containing compounds, whose exact structure was unknown. Nonetheless, all free isocyanate groups in these samples were quantitated based on the observed UV absorbance at the wavelengths specific for MAMA. In comparison to a reference titration procedure using di-n-butylamine, analytical recovery of TRIG in these samples ranged from 95 to 107 % .

The dichotomous sampler for TRIG aerosol and vapor consisted of an impactor or cyclone inlet for collection of non-respirable aerosols followed by an annular diffusional denuder tube for collection of vapor and backed up by a treated filter or impinger for collection of respirable aerosol. The initial evaluation of the device used denuders and backup filter coated with Nitro Reagent and was conducted with test atmospheres of MDI vapor and condensation aerosol. Separation of the MDI into vapor and aerosol fractions by the dichotomous sampler correlated very well with the formation of aerosol as a function of concentration as predicted by the saturated vapor pressure of MDI and as measured independently by a light scattering aerosol monitor. The performance of the annular denuder in terms of collection efficiency for aerosol and vapor of MDI matched well with the theoretical prediction of 94% collection efficiency for MDI vapor and essentially complete penetration by MDI condensation aerosol. Adaptation of the device for measurement of TRIG involved coating of the denuders and backup with MAMA reagent and tributylphosphate to aid in vapor collection efficiency. The device efficiently collected vapor and aerosol forms of the eleven isocyanate monomers examined except for methylisocyanate, the most volatile of the group. Sampling of test atmospheres of HDI and MDI oligomers produced by nebulization showed partitioning of the monomers between vapor and condensed phases. The oligomers of HDI did not partition between the phases but rather were found only in the condensed aerosol phase. One particular oligomer of MDI which was not definitively identified partitioned between the vapor and aerosol phases in a fashion similar to that of MDI. The remaining oligomers, amounting to about 80% of the TRIG, were found in the condensed aerosol phase only.

Workplace sampling with the dichotomous sampler was conducted during polyurethane paint spray applications and during the manufacture of flexible polyurethane foam products. The paint spray operations utilized a two part paint based on HDI. Measured levels of TRIG during the spraying operation averaged $391 \pm 154 \mu\text{g}/\text{m}^3$. HDI concentrations averaged only $14 \pm 6.5 \mu\text{g}/\text{m}^3$. HDI-biuret was the largest component of TRIG found in these samples and was completely in the condensed aerosol phase. The majority of the HDI was measured in the vapor phase, but significant (15 - 26%) amounts were measured in the aerosol fraction of the paint overspray. Both TDI and MDI were used in the polyurethane foam formulations. However only TDI (up to $129 \mu\text{g}/\text{m}^3$) and some apparently low molecular weight TRIG compounds (up to $4.7 \mu\text{g}/\text{m}^3$) were measured in the atmosphere. Most of these materials were found to be in the vapor phase. TDI and TRIG were also detected in several foam finishing processes which subject the cured polyurethane foam to high temperature, indicating potential regeneration of isocyanate from thermal decomposition of polyurethane.

4.) Background

The isocyanates are an important group of commercial chemicals used in the production of polyurethanes and certain carbamate pesticides. These compounds are of particular interest in industrial hygiene due to their well-documented ability to act as respiratory irritants, skin sensitizers, and respiratory sensitizers. Recently, there has been increasing interest in the environmental behavior and potential health effects of total reactive isocyanate group (TRIG). TRIG represents all free isocyanate chemical groups present in the work environment, whether due to mono-, di-, or poly-isocyanate compounds, including the parent monomeric diisocyanate compounds common in industry. TRIG compounds may be emitted into the workplace

atmosphere in a variety of ways: (1) as unreacted monomeric diisocyanate (e.g., 2,4- and 2,6-toluenediisocyanate [TDI], 4,4'-diphenylmethane-diisocyanate [MDI], 1,6-diisocyanatohexane [HDI]) offgassing from production lines, spills, etc.; (2) as unreacted oligomeric isocyanate compounds mechanically introduced into the atmosphere from spray application of polyurethane coatings and foams, e.g., HDI-biuret and polymethylene-polyphenyl-isocyanate (PMPPi); (3) as partially reacted isocyanate compound being emitted from industrial products, or being formed from reaction of isocyanate with water vapor, ammonia, or other airborne chemicals containing labile hydrogen; and (4) as mixtures of vapor and aerosol isocyanate compounds produced from the thermal degradation of isocyanate based products, principally polyurethane plastics and coatings.

For the first case listed above a data base on health effects and environmental levels of monomeric diisocyanates has been steadily building since the commercial introduction of TDI in 1947. This knowledge base is reflected in the histories of governmental regulations and trade group guidelines concerning isocyanate exposure. These show temporal trends of steadily decreasing allowable exposure levels and the inclusion of the non-traditional isocyanate compounds. On the other hand, the latter three sources of TRIG represent the potential for more insidious exposure of workers to isocyanate. While the health effects of exposure to monomeric diisocyanate are well-known, and current research efforts are aimed at refining the dose-response relationship, little information has been developed concerning exposure to TRIG. This is partially due to the lack of well-documented methods of determining TRIG in air with a suitable level of accuracy and precision, and also due to the related lack of specific exposure standards for TRIG in most of the industrialized world.

Little information exists in the literature which directly relates exposure to TRIG with observed health effects. Animal models have indicated HDI-biuret to be a potent pulmonary irritant, and have suggested an allowable exposure level of about 0.5 mg/m^3 .⁽¹⁾ There are many case reports in the literature linking exposure to polyisocyanates -- primarily from spray painting -- to various pulmonary diseases, including asthma⁽²⁾ and hypersensitivity pneumonitis.^(3,4) In contrast, there are currently no population-based studies in the literature directly concerning chronic TRIG exposure-related health effects.

In a study of polyurethane foam plants performed by the principal investigator's group,⁽⁵⁾ large excess annual declines in lung function were noted among the production workers; however, this change was not statistically related to exposure to TDI, either cumulatively or during the five-year study period. It is possible that the presence of TRIG in the workplace atmosphere may play a part in explaining these results. The exposure monitoring methodology was set up only for measurement of TDI, which was detected in the foaming area due to offgassing from fresh foam, and at lower levels in the finishing areas. The source of the latter was presumably due to general contamination of the plant atmosphere, and also from various finishing processes which pyrolytically decomposed foam (flame and hot-roll lamination and "zapping"/reticulation).^(6,7) Monomeric TDI was clearly detected in the smokes emanating from these hot processes. It seems plausible that other forms of TRIG were also present in these smokes, but were not detected with our methodology. If present, TRIG compounds could have confounded an analysis based only on TDI exposure, particularly if TRIG levels do not correlate with those of TDI monomer.

In another relevant report from the literature, an outbreak of respiratory disorders (wheezing, shortness of breath), including one clear case of isocyanate asthma, occurred among 203 workers in an automobile seat manufacturing plant upon converting to a product consisting of a polyurethane foam backing flame laminated to a nylon substrate.⁽⁸⁾ Low levels of TDI (0.3- 3 ppb) were detected emanating from this product during cutting and sewing operations. It seems unlikely that TDI at these low levels could have resulted in the widespread occurrence of acute respiratory symptoms reported. The possibility that this product contained non-TDI forms of TRIG trapped in the foam/nylon flame laminate, which were emitted into the workplace and contributed to the health problems, cannot be discounted.

In support of this, high-temperature pyrolysis of polyurethane in the laboratory has been shown to release a variety of isocyanate compounds. Polyether and polyester TDI-based foams were shown to release monomeric TDI as the only nitrogen-containing compound at 200-300°C; whereas, above 800°C, a variety of nitrogen compounds were obtained, including pyridine, organic cyanides, and HCN.⁽⁹⁾ PMPPi-based polyurethane foundry binders were shown to release phenylisocyanate, p-tolylisocyanate, and MDI monomer under high-temperature pyrolysis.⁽¹⁰⁾ In addition, even low-temperature heating (80°C) of PMPPi-based rigid foam was shown to release butylisocyanate.⁽¹¹⁾ Thus, industrial processes which heat polyurethanes to elevated temperatures are potentially very significant sources of insidious TRIG exposure.

Currently, the Health and Safety Executive (HSE) of the United Kingdom has the only explicit standard regarding TRIG.⁽¹²⁾ Their approach has been to assume that the isocyanate (NCO) functional group is inherently responsible for observed health problems associated with exposure, regardless of the organic moiety to which the isocyanate group is attached. Thus, the allowable exposure level is 20 µg NCO per m³ of air, which is simply based on an extrapolation of the equivalent TRIG level for 2,4-TDI, the standard for TDI being 40 µg/m³, and there being 0.48 µg TRIG per µg TDI.

Initial methods developed for analysis of TRIG were adaptations of working methods for monomeric diisocyanates. NIOSH developed a method using 1-(2-methoxyphenyl)-piperazine (MOPIP) to form urea derivatives with all available TRIG.⁽¹³⁾ The method involved sampling with an impinger containing a known amount of MOPIP in toluene. After sampling, the remaining MOPIP was quantitated by HPLC, and the change in MOPIP concentration used to calculate TRIG equivalents. The method had several serious problems: (1) a small change in a large excess concentration of MOPIP had to be determined -- this required an extraordinary degree of analytical precision; and (2) physical losses of MOPIP occurred through volatilization and partitioning into aqueous condensate in the impinger, which confounded TRIG estimation.⁽¹⁴⁾ These problems led NIOSH to withdraw the method from recommendation.⁽¹⁵⁾

The United Kingdom's HSE modified the MOPIP method to eliminate the problems described above. The HSE's Method MDHS 25⁽¹⁶⁾ also uses MOPIP in solution in an impinger. All TRIG compounds react with the MOPIP to form urea derivatives which absorb in the UV, and are electrochemically active and can be separated by HPLC. For a given diisocyanate monomer and its oligomers, a constant ratio between UV absorbance and electrochemical detector response will be obtained. Thus, a peak on the HPLC chromatogram can be identified as a specific TRIG oligomer using the specific monomer as a standard. Total TRIG content of a sample can be estimated from combining the electrochemical response of all peaks, and comparing it to standards made from the parent monomer compound.

While a significant improvement over the original MOPIP method, the technique is still characterized by problems with specificity and the inability to deal with TRIG derived from more than one parent monomer.⁽¹⁷⁾ In addition, TRIG compounds which are not simple oligomers of a given monomeric diisocyanate, such as might be found in polyurethane pyrolysis fumes, cannot be accurately quantified, since they may have no direct relationship to the analytical response of the monomer standard. Nonetheless, it is an operational method in the UK.

Another technique for determination of TRIG uses 9-(N-methylaminomethyl)-anthracene (MAMA) as the derivatizing agent. Analysis of MAMA-isocyanate ureas is by HPLC with UV and fluorescence detection.⁽¹⁸⁾ The method was used with some success to measure isocyanate monomer and oligomer in paint overspray,⁽¹⁹⁾ and TRIG from thermal degradation of polyurethane binders.⁽¹⁰⁾

A more recent technique for TRIG uses 3-(2-aminoethyl)indole (tryptamine or TRYP) as the derivatizing agent for TRIG. Determination of the TRIG-TRYP urea derivatives is accomplished with HPLC, and fluorescence and amperometric detection.^(20,21) TRYP has the advantage that the fluorescence and amperometric response of the ureas is dictated by the indole unit from TRYP, and is not influenced by the nature of the organic moiety of the TRIG group. Thus, a constant ratio of the two detectors is expected regardless of the TRIG parent compound. This also allows TRYP itself to be used for standardizing the analytical response. The method, using TRYP in solution with impinger collection, was evaluated for analysis of methylisocyanate (MIC)⁽²⁰⁾ and PMPPi⁽²¹⁾ in the laboratory, and shown to have suitable sensitivity and selectivity for workplace exposure monitoring.

The use of impingers or treated filters for all of the above methods is a shortcoming in that impingers are inefficient sampling devices for submicron aerosols, particularly when the impinger is not operated at its optimum flow of 2.8 Lpm. On the other hand, treated filters may not reliably collect very volatile forms of TRIG, such as MIC and phenylisocyanate. In any case, neither technique provides information on the physical state of collected TRIG (vapor or condensed phase). The question of the physical state of airborne TRIG and monomeric diisocyanates is currently an important topic both in terms of appropriate analytical and exposure control methodologies, and in biological effects as a function of site of respiratory deposition.⁽²²⁻²⁵⁾

The vapor/aerosol partitioning of isocyanate compounds arises from two sources: (1) the wide range in vapor pressures of the compounds and (2) their relatively high degree of surface affinity. The polymeric isocyanates (polymerized MDI, HDI-biuret) are essentially non-volatile, and will exist only as mechanically generated aerosols in the atmosphere. In contrast, at 25°C, monomeric MDI has a vapor pressure equivalent to an airborne concentration of 9 ppb.⁽²⁶⁾ This is less than half the OSHA PEL (20 ppb); thus, occupational exposures to MDI are commonly to a mixture of the gaseous and particulate phases, depending on temperature. The vapor pressures of TDI and HDI at 25°C are equal to concentrations of about 40 and 30 ppm, respectively.⁽²⁷⁾ These levels are greater than 1,000 times the PEL/STEL of 5 ppb/20 ppb. Finally, at the upper end of the range of volatility of isocyanates, methylisocyanate (MIC) has a vapor pressure of 348 mm Hg at 20°C, equivalent to about 458,000 ppm. Thus, for MIC, and even TDI and HDI, occupational exposures would be expected to be primarily to the vapors of these compounds under normal circumstances.

On the other hand, although its vapor pressure is large relative to the exposure standard, TDI has been recognized as having a high affinity for surfaces; for example, several studies on the kinetics of hydrolysis of TDI have shown that the reaction with water occurs primarily on the surfaces of the vessel containing the test atmosphere of TDI and water vapor.^(28,29) Our own experience is that significant amounts of TDI adsorb onto available surfaces, as evidenced by the time required to reach steady-state airborne concentrations in various test systems. The question arises as to whether this surface affinity is important when TDI exists in a mixed atmosphere with particulate matter. It is postulated that vapor phase TDI would be in equilibrium with significant amounts of TDI adsorbed onto the particle surfaces. Similar behavior could be anticipated for other forms of TRIG, particularly in association with smokes from thermal decomposition of polyurethanes. These questions have not yet been addressed by experimentation in the laboratory or field.

The partitioning of TRIG into vapor and aerosol fractions could prove of great importance in relation to the observed health effects of over-exposure. The deposition pattern of the isocyanates during inhalation has not yet been determined, although it could be speculated that adsorption occurs down the length of the respiratory tract. Thus, it is possible that under certain circumstances little isocyanate vapor ultimately reaches the alveolar compartment. On the other hand, if the isocyanate is present as respirable sized condensation aerosol or is adsorbed onto respirable particles, direct deposition in the alveoli is probable. It is of interest to note that the majority of cases of hypersensitivity pneumonitis induced by diisocyanate exposure have been associated with MDI. The requirement of direct delivery of the antigen to the lower respiratory system for induction of hypersensitivity pneumonitis, coupled with the likelihood of MDI existing as an aerosol, points to the importance of the physical state of the diisocyanate in the observed toxicity of exposure. In contrast, the induction of asthma does not require this intimate contact of the etiologic agent with the deepest parts of the respiratory system.

Overall, little work has been done concerning the aerosol/vapor partitioning of isocyanates. The first recognition of the potential problem came in relation to sampling of MDI during spray applications of polyurethane foam, and in laboratory test atmospheres of MDI produced by heating the material in an enclosed space.^(22,23) In either case, impinger sampling according to the then-current NIOSH standard method^[30] resulted in lower estimates of concentration than a commercially available paper tape instrument. In addition, when a filter unit was placed upstream of the impinger inlet, a large percentage of the airborne MDI was removed from the air stream by the filter. Since the efficiency of the midget impinger rapidly decreases for particles less than 0.75 μm AED,^[31] these results clearly indicated the vapor/aerosol partitioning of MDI. This result could have been anticipated for the foam spraying application where some free MDI would be expected in the matrix of partially unreacted polyurethane foam particulates. For the thermally generated laboratory test atmospheres (about 20 ppb MDI), the results were inconsistent with then-available data on the vapor pressure of MDI^[27] which predicted no steady-state aerosol formation below about 200 ppb at 25°C. Since then, this value has been revised downward to approximately 9 ppb, as indicated in the above discussion.

The use of a combination of an untreated filter and impinger described above is an inappropriate technique for accurate dichotomous sampling of MDI. Due to its finite vapor pressure, MDI collected on the filter would tend to vaporize when sampling continues in a less

than saturated atmosphere. In addition, its reactive nature dictates using a technique which rapidly stabilizes MDI as a derivative upon collection. Treating the filter to achieve the latter would also result in efficient collection of the vapor phase, negating the ability to differentiate between the phases. A special symposium at the American Industrial Hygiene Conference in Montreal (June, 1987) was devoted specifically to the problems of sampling for airborne diisocyanates. However, up to this point, little effort has been directed toward the development of dichotomous sampling techniques for the separation and quantitation of isocyanate aerosol and vapor.

Thus, a specialized sampling apparatus is needed for dichotomous collection of mixtures of vapor and condensed phase MDI, and, indeed, the other diisocyanates and TRIG as well. In this work diffusional denuder sampling has been applied to dichotomous measurement of TRIG. The diffusional denuder takes advantage of the huge difference in diffusivity of gases and submicron particles to effect a quantitative separation of the two.^[32] Thus, by using a flow column whose wall acts as a perfect adsorbent, gases diffuse from the sample during passage and collect on the wall; whereas, due to their much smaller diffusivities, particles pass through and are collected by a final filtration device. Original designs of denuder tubes used simple flow tubes for construction; more recent designs use an annular denuder consisting of coaxial inner and outer cylinders, with the air flowing through the annular space between. The annular configuration provides the advantages of much higher flow rates, shorter column lengths, and improved collection efficiencies as compared to the tubular denuder.

The operation of tubular denuders was analyzed by Gormley and Kennedy⁽³³⁾ and described mathematically as follows:

$$P = 0.819 e^{[-3.66 \mu]} + 0.098 e^{[-22.3 \mu]} + 0.033 e^{[-57.0 \mu]} \quad 1$$

where P is the penetration fraction through the denuder, and μ is a dimensionless number relating the diffusion coefficient D, channel length L, and flow rate Q:

$$\mu = \frac{\pi D L}{Q} \quad 2$$

However, when μ is very small, such as for aerosols, then the penetration fraction is modeled as:

$$P = 1.0 - 2.56 \mu^{2/3} + 1.2 \mu + 0.177 \mu^{4/3} \quad 3$$

In a similar fashion, Possanzini, *et al.*,⁽³⁴⁾ examined the penetration of diffusing species through an annular denuder. In this case, an equivalent expression for the annular configuration was developed for the dimensionless value in the exponential terms, with

$$\mu' = \frac{\pi D L (d_1 + d_2)}{4 Q (d_2 - d_1)}$$

4

Here, d_1 and d_2 are the inner and outer diameters of the annulus, respectively. For gases, the magnitude of μ' is such that only the first term in equation 1 is significant. Possanzini determined the value of the constants in this first term to be 0.82 ± 0.10 , and -22.53 ± 1.22 , for an annular denuder collecting sulfur dioxide.⁽³⁴⁾

The annular denuder was initially developed for selective sampling of sulfur dioxide in mixed aerosol atmospheres⁽³⁴⁾ using denuder walls coated with tetrachloromercurate. Sorption efficiency was greater than 98% for SO_2 . Later, the same denuder was modified for the removal of interfering gaseous oxides of nitrogen when sampling for particulates;⁽³⁵⁾ for the sampling of tetraalkyllead mixed with inorganic lead salt particulates,⁽³⁶⁾ and for the collection of formaldehyde vapor using bisulfite-triethanolamine coated denuder walls.⁽³⁷⁾

More recently, the annular denuder has become an important tool for assessing acid air pollution.⁽³⁸⁻⁴¹⁾ In this area, it has been particularly useful for separation of gaseous species, such as ammonia, which present analytical interference in the analysis of collected acid aerosol.^(42,43) Various inlet designs, including impactor plates and cyclones, have been developed which enable pre-separation of non-respirable particles from the sample stream, thus eliminating potential problems arising from the deposition of coarse particulates on the walls near the inlets of the denuder.^(44,45)

Based on these favorable characteristics, this project applied TRIG detection technology to the dichotomous sampling of vapor/aerosol isocyanates using an annular denuder. A well characterized, commercially available annular denuder system was modified for this purpose.

5.) Specific Aims

The specific aims of this project were:

- (1) to compare the performance of the methoxy-phenylpiperazine (MOPIP), methylamino-methylanthracene (MAMA), and tryptamine (TRYP) methods for TRIG in terms of selectivity, sensitivity, accuracy, and precision of analysis, using a series of model aliphatic and aromatic isocyanate compounds;
- (2) to adapt the best of these techniques to dichotomous sampling of condensed and vapor phase TRIG using an annular diffusional denuder sampling device;
- (3) to perform a thorough evaluation of the performance of the dichotomous sampler in the laboratory;
- (4) to use the dichotomous TRIG sampler to evaluate TRIG levels and physical state in representative workplaces.

6.) Studies and Results

a. Comparison of MOPIP, MAMA and TRYP Procedures for Measurement of TRIG

Analytical derivatives of eleven isocyanate compounds with MAMA, MOPIP, and TRYP were synthesized in the laboratory. The isocyanates utilized were methylisocyanate (MIC), butylisocyanate (BUT), phenylisocyanate (PIC), benzylisocyanate (BEN), o-tolylisocyanate (OTOL), p-tolylisocyanate (PTOL), 1,6-hexamethylenediisocyanate (HDI), 2,4-toluenediisocyanate (2,4-TDI), 2,6-toluenediisocyanate (2,6-TDI), methylene-bis-(4,4'-cyclohexylisocyanate) (HMDI), methylene-bis-(4,4'-phenylisocyanate) (MDI). Originally, two oligomeric isocyanates (HDI-biuret and poly-methylene-poly-phenylisocyanate) were also to be included in this initial work. However, problems were encountered in trying to purify the prepared derivatives from these materials since they are by nature heterogeneous mixtures of various isocyanate containing compounds. In light of this, assessment of the oligomeric isocyanates was performed as a separate series of experiments and is discussed later in this report.

The syntheses of the 33 isocyanate-urea derivatives were similar for all and involved mixing of the isocyanate with an excess of the amine derivatizing agent in a suitable solvent and allowing the reaction to proceed at room temperature. Typically, the urea derivative would fall out of solution and be recovered by filtration. After synthesis, the 33 urea derivatives were purified by recrystallization or column chromatography and their identities were confirmed by elemental analysis and infrared spectroscopy, and, where needed, proton-NMR and mass-spectroscopy.

Derivatives of MOPIP and MAMA were straightforward to synthesize, and were readily purified by recrystallization. TRYP derivatives were found to be more difficult to prepare. There was some evidence of multiple addition of isocyanate to the primary amine of TRYP. This necessitated use of large excess of TRYP in the synthesis of some of these compounds. This problem was most evident for the unhindered aromatic isocyanates. The solubilities of TRYP and the TRYP ureas appeared to be somewhat similar, so that recrystallization was often ineffective, and column chromatography on silica gel had to be employed for purification of derivative in many cases.

After purification and confirmation, the analytical response of each of the derivatives was compared for consistency within a given derivatizing agent. Equimolar amounts of each derivative based on original isocyanate content were analyzed by reversed-phase HPLC on an octadecyl bonded phase column with an acetonitrile, acetate-buffer mobile phase. Chromatographic conditions were adjusted to simply separate the compound of interest from the eluting solvent front. For each of the derivatizing agent groups, analytical response was examined with three detection modes which were chosen based on data from the literature^(16,18,20) and optimized by in-house experimentation:

- MAMA derivatives were analyzed using fluorescence with excitation at 245 nm and emission at 414 nm, and UV absorbance at two wavelengths, 245 and 370 nm.
- MOPIP derivatives were analyzed with electrochemical detection at a potential of 0.8 V, and UV absorbance at two wavelengths, 242 and 277 nm.

- TRYP derivatives were analyzed with fluorescence at an excitation of 272 nm and an emission of 344 nm, with electrochemical detection at a potential of 0.8 V, and with UV absorbance at 280 nm.

For each analysis, a response factor (RF) was calculated as the ratio of the integrated chromatographic peak area to the sample concentration expressed in millimoles of isocyanate equivalence per liter (mM NCO). The results of these evaluations are shown in Tables 1 - 3.

ANOVA and Kruskal-Wallis ANOVA were performed on the three detection modes for each of the derivatizing agent to assess consistency across the eleven isocyanate compounds. There were statistically significant differences among the isocyanates for every derivatizing agent / detection mode combination. The derivatizing agent / detection mode combinations showing the most variability as measured by the relative standard deviation (RSD) of the mean RF with equal weighting for all isocyanates were: TRYP / electrochemical detection with a RSD of 71%, MAMA / fluorescence with a RSD of 55%, and MOPIP / UV 242 nm with a RSD of 53%. The derivatizing agent / detection mode combinations showing the most consistency across isocyanates were MAMA / UV 370 nm with a RSD of only 8.6%, and MAMA / UV 245 nm with a RSD of 14%.

Table 1
Analytical Response (RF: Response Factor) of MOPIP Derivatives of Model Isocyanates

Isocyanate	RF x 10 ⁻⁵ UV, 242 nm	RF x 10 ⁻⁵ UV, 277 nm	RF x 10 ⁻⁵ Electrochemical Detection
2,4-TDI	4.04 ± 0.30	9.44 ± 0.77	7.34 ± 0.36
2,6-TDI	5.83 ± 0.19	14.0 ± 0.44	11.9 ± 0.42
BEN	5.50 ± 0.44	5.28 ± 0.14	5.92 ± 0.33
BUT	3.27 ± 0.20	14.2 ± 0.85	9.07 ± 0.11
HDI	2.80 ± 0.18	12.3 ± 0.64	10.5 ± 0.67
HMDI	3.11 ± 0.08	13.1 ± 0.55	7.80 ± 0.13
MDI	6.83 ± 0.25	24.7 ± 0.71	14.5 ± 0.65
MIC	4.00 ± 0.12	17.0 ± 0.53	12.7 ± 0.38
OTOL	7.36 ± 0.33	17.2 ± 0.85	8.57 ± 0.28
PIC	11.8 ± 1.16	18.4 ± 1.7	9.47 ± 0.50
PTOL	11.5 ± 0.51	19.4 ± 0.84	11.6 ± 0.91
Overall	6.00 ± 3.17 (53%)	15.0 ± 5.2 (35%)	9.94 ± 2.56 (26%)

Table 2
Analytical Response (RF: Response Factor) of TRYP Derivatives of Model Isocyanates

Isocyanate	RF x 10 ⁻⁶ UV, 280 nm	RF x 10 ⁻⁶ Fluorescence $\lambda_{\text{excitation}} = 272 \text{ nm}$ $\lambda_{\text{emission}} = 344 \text{ nm}$	RF x 10 ⁻⁷ Electrochemical Detection
2,4-TDI	3.80 ± 0.16	6.04 ± 0.36	9.27 ± 0.44
2,6-TDI	3.60 ± 0.19	6.70 ± 0.39	5.89 ± 1.19
BEN	2.78 ± 0.21	9.86 ± 0.58	2.20 ± 0.16
BUT	4.37 ± 2.18	11.2 ± 0.52	7.49 ± 3.80
HDI	2.50 ± 0.09	6.84 ± 0.09	3.51 ± 0.16
HMDI	2.82 ± 0.21	8.86 ± 0.62	1.19 ± 0.36
MDI	3.87 ± 0.17	10.4 ± 0.53	2.11 ± 0.13
MIC	1.58 ± 0.07	4.01 ± 0.17	3.33 ± 0.15
OTOL	3.18 ± 0.20	9.10 ± 0.65	1.47 ± 0.17
PIC	3.78 ± 0.42	10.4 ± 1.2	2.33 ± 0.28
PTOL	3.40 ± 0.17	8.44 ± 0.52	2.27 ± 0.76
Overall	3.24 ± 0.78 (24%)	8.35 ± 2.21 (26%)	3.73 ± 2.65 (71%)

Table 3
Analytical Response (RF: Response Factor) of MAMA Derivatives of Model Isocyanates

Isocyanate	RF x 10 ⁻⁷ Fluorescence $\lambda_{\text{excitation}} = 245 \text{ nm}$ $\lambda_{\text{emission}} = 414 \text{ nm}$	RF x 10 ⁻⁷ UV, 245 nm	RF x 10 ⁻⁶ UV, 370 nm
2,4-TDI	2.77 ± 0.14	3.34 ± 0.09	3.09 ± 0.06
2,6-TDI	7.78 ± 0.25	3.40 ± 0.06	3.32 ± 0.18
BEN	11.0 ± 0.42	2.92 ± 0.10	2.97 ± 0.13
BUT	10.7 ± 0.39	2.97 ± 0.06	2.89 ± 0.09
HDI	3.42 ± 0.11	2.39 ± 0.08	2.44 ± 0.09
HMDI	7.88 ± 0.49	2.54 ± 0.16	2.80 ± 0.15
MDI	3.35 ± 0.08	3.47 ± 0.14	3.18 ± 0.22
MIC	11.1 ± 0.35	3.18 ± 0.24	3.22 ± 0.55
OTOL	10.4 ± 0.44	3.31 ± 0.13	3.22 ± 0.12
PIC	3.10 ± 0.10	3.75 ± 0.16	3.16 ± 0.13
PTOL	2.77 ± 0.13	3.77 ± 0.23	3.17 ± 0.26
Overall	6.74 ± 3.68 (55%)	3.19 ± 0.45 (14%)	3.02 ± 0.26 (8.6%)

Although ANOVA of the two MAMA / UV absorbance groups indicated statistically significant differences among the isocyanates, Scheffe's multiple comparison procedure identified only two homogeneous groups among the mean RF's for UV absorbance at 370 nm. One of these homogeneous groups contained all the isocyanates except HDI. UV absorbance at 245

nm exhibited more inherent variability, with Scheffe's procedure identifying seven different homogeneous groups among the eleven isocyanates. The range of RF's for this detection mode covered a factor of 1.6 from the lowest (HDI, $RF = 2.39 \times 10^7$) to the highest (PTOL, $RF = 3.77 \times 10^7$). For UV absorbance at 370 nm, the range between lowest (HDI, $RF = 2.44 \times 10^6$) and highest (2,6-TDI, $RF = 3.32 \times 10^6$) was only a factor of 1.36.

The ratios of the RF's for the two UV absorbance detection modes of the MAMA isocyanate derivatives are presented in Table 4. Overall, there were statistically significant differences in this value across the eleven isocyanates when examined by ANOVA; however, the overall variability as indicated by the CV of the mean RF was only 8.3%. Scheffe's procedure identified three homogeneous groups among the eleven means. One of these groups contained all of the isocyanates except HMDI and PTOL. The range of RF's from the lowest (HMDI, ratio = 9.1) to highest (PTOL, ratio = 11.9) was a factor of 1.31.

Table 4
Ratio of Response Factors for UV Absorbance by MAMA Derivatives of Model Isocyanates

Isocyanate	RF Ratio UV 245 nm : UV 370 nm
2,4-TDI	10.8 ± 0.2
2,6-TDI	10.3 ± 0.2
BEN	9.8 ± 0.1
BUT	10.3 ± 0.2
HDI	9.8 ± 0.3
HMDI	9.1 ± 0.2
MDI	10.9 ± 0.5
MIC	10.0 ± 1.0
OTOL	10.3 ± 0.2
PIC	11.9 ± 0.1
PTOL	11.9 ± 0.6
Overall	10.5 ± 0.9 (8.3%)

Careful review of the results from this initial screening of MOPIP, TRYP and MAMA led to the selection of MAMA as the derivatizing agent of choice for development and evaluation as a chemical label for TRIG and incorporation into the dichotomous sampler. MAMA derivatives of the test isocyanates exhibited the most consistency in RF for detection by UV absorbance at 245 nm and 370 nm. The ratio of RF's for these two detection modes was remarkably consistent. This RF ratio could be used to identify TRIG containing compounds in MAMA treated samples; further, while there was a wide variability in RF for fluorescence detection of the MAMA isocyanate derivatives, all were highly fluorescent. Thus fluorescence could be used as an additional confirmation of the identity of a TRIG derived peak during chromatographic analysis of samples.

b. Application of MAMA to Measurement of TRIG in Oligomeric Isocyanate Materials

As a further demonstration of the utility of the MAMA technique for measurement of TRIG, the technique was applied to the assay of isocyanate content of a series of commercial materials containing oligomeric isocyanates and polyurethane precursors. The following materials were evaluated in this phase of the study:

- **CMDI**, obtained from BASF Corp., Geismar, LA. This material nominally contains 58 - 68 % MDI monomer, with the remainder being oligomers of MDI.
- **Lupranate M20S**, obtained from BASF Corp., Geismar, LA. This material nominally contains 40% MDI monomer, and 60% MDI oligomers.
- **PMPPI [poly(methylene(polyphenylisocyanate))]**, obtained from Aldrich Chemical Co. This material is an oligomeric form of MDI.
- **Desmodur N100**, obtained from Mobay Corp., Baytown, TX. This is a homopolymer of HDI, with HDI-biuret (a trimer of HDI) being predominant. A maximum of 1.6% HDI monomer is expected after 3 to 6 months storage. The material was approximately 18 months in storage when used in this work.
- **Imron paint activator 192S**, manufactured by DuPont Automotive Products, Wilmington, DE. This material is a solution of about 33% HDI oligomers in butyl acetate, ethyl acetate, and trimethylbenzene.
- **Rexthane**, manufactured by the Sherwin-Williams Co., Cleveland, OH. This is a moisture-curing, heavy duty, polyurethane varnish containing 2,4- and 2,6-TDI monomers, polyurethane prepolymers (polyhydric alcohols modified with TDI), and xylene.

The isocyanate content of the study materials was first determined using a standard titration procedure based on reaction of isocyanate with di-n-butylamine.⁽⁴⁶⁾ An aliquot of the test material (0.5 to 1 g) was weighed out and subsequently dissolved in 6 mL toluene previously dried over molecular sieve 5A. To the sample was added 2.0 N di-n-butylamine in toluene at a ratio of 7.5 mL to 1 gram of isocyanate-containing material. The sample was loosely capped and allowed to react for 15 minutes. Thirty-four mL of isopropanol were then added to the mixture, along with 75 μ L bromocresol green indicator solution (0.1% in 0.02 N NaOH). The excess di-n-butylamine was then titrated with standardized HCl solution, (~1.0 N). The isocyanate content of the test materials was calculated based on the number of equivalents of di-n-butylamine consumed during reaction in comparison to a reagent blank:

$$wt\%NCO = \frac{4.2N(B - S)}{W} \quad 5$$

where N = normality of the HCl titrant,
B= volume of HCl required for titration of reagent blank,
S = volume of HCl required for titration of sample,
and W = mass of sample assayed.

In order to assay the test materials for TRIG content using the MAMA technique, reaction of the isocyanate containing materials with MAMA reagent was carried out as follows: a known mass of test material (0.1- 0.3 grams) was weighed out and dissolved in an appropriate solvent (dioxane for the MDI-based materials, 50/50 dioxane/dimethylformamide for Imron 192S, and dimethylsulfoxide for Desmodur N100 and Rextthane). The expected number of moles of isocyanate present were calculated based on the results of the reference assay. The samples were then reacted with a 3 to 5 fold excess of MAMA, based on a stoichiometric reaction of one mole of MAMA with one mole of isocyanate group. The MAMA reagent was dissolved in the same solvent as the isocyanate-containing material prior to its addition. After allowing sufficient time for reaction, the samples were submitted for analysis by HPLC.

Chromatographic analysis of the MAMA-derivatized samples and standards was performed with detection by fluorescence using a Shimadzu Model RF551 fluorometric detector with excitation at 245 nm and emission at 414 nm, and by ultraviolet absorption at two wavelengths using a Perkin Elmer Model LC90 UV detector set at a wavelength of 245 nm and a Waters Model 450 UV detector set at a wavelength of 370 nm. Sample injection volumes were defined by a 20- μ L sample loop. Samples were analyzed on a Supelcosil LC-8-DB octyl bonded phase column, 5 μ m particle size (Supelco, Belafonte, PA), 4.6 mm i.d. by 5 cm long. The mobile phase consisted of a mixture of acetonitrile and aqueous triethylammonium phosphate buffer (3% triethylamine in water, adjusted to pH 3.0 with phosphoric acid). The acetonitrile concentration was adjusted to ensure chromatographic separation of excess MAMA reagent and the individual isocyanate containing compounds in the samples, while minimizing chromatographic run times for the late eluting compounds. A concentration of 60% acetonitrile in the mobile phase at a flow rate of 1 mL/min was utilized for the HDI-based samples; for analysis of the Rextthane sample, a mobile phase containing 54% acetonitrile was used at an initial flow rate of 2 mL/min which was increased to 4 mL/min after the elution of the TDI monomers. For the MDI-based materials, a mobile phase containing 60% acetonitrile was used at an initial flow rate of 1 mL/min for 22 minutes to allow elution of the MDI monomer and one oligomer, and then was increased to 2 mL/min. For those cases where the mobile phase flow rate was increased during a chromatography run, the measured areas of peaks of interest were corrected for the proportional change in integrated detector response due to the resulting reduction in residence times in the detectors.

Chromatograms were screened for presence of TRIG-derived peaks by comparison to the respective isocyanate parent monomer standard. The criteria for classification of a peak as being of TRIG origin was a detector response ratio for UV absorbance at 245 nm to that at 370 nm within $\pm 20\%$ of that for the monomer standard. The 20%-criteria was derived as an approximation of the 95% confidence interval of the overall mean RF ratio observed for the eleven different isocyanate monomers as presented in Table 4. Further confirmation of the identity of an unknown TRIG containing compound was provided by examination of its fluorescence response. In general, the fluorescence of the identified TRIG compounds was of the same order of magnitude as their corresponding diisocyanate monomer standards, although there appeared to be a general trend of decreasing fluorescence with increasing chromatographic retention time.

After identification of a TRIG compound, the amount of isocyanate present was determined in comparison to the response of the parent monomer standard. This was done for each of the UV absorbance detectors independently. Calibration of detector response for quantitation of

TRIG in these compounds used conversion factors based on two moles TRIG / mole of diisocyanate monomer standard; i.e., for MDI, 0.121 $\mu\text{g TRIG} / \mu\text{g MDI-MAMA-urea}$; for HDI, 0.138 $\mu\text{g TRIG} / \mu\text{g HDI-MAMA-urea}$; and for 2,4- and 2,6-TDI, 0.136 $\mu\text{g TRIG} / \mu\text{g TDI-MAMA-urea}$. In order to quantitate TRIG in the Rextthane sample, an average calibration curve was generated by combining the data for the 2,4- and 2,6-TDI standards and performing a linear regression of detector response vs. concentration with equal weighting for the responses of 2,4-TDI and 2,6-TDI.

Figures 1 through 3 present representative chromatograms from each of the three classes of oligomeric isocyanates. In each case, excess MAMA reagent elutes at the beginning of the chromatogram, with MAMA-derivatized isocyanate-containing compounds, including that from the respective parent monomers, eluting later. The parent isocyanate monomers are the first eluting compounds of interest in each sample. Later eluting compounds are presumably either oligomers of the parent monomer isocyanate or polyurethane prepolymers formed by reaction of isocyanate with polyols or water.

All three of the MDI-based materials contained significant amounts of MDI monomer, identified as peak number 1 in the chromatogram of the CMDI sample (Figure 1) and in Table 5, which presents the results of the assays of each of the test materials. CMDI contained MDI monomer as well as two other peaks identified as isocyanate compounds. While the third peak actually appeared to be two unresolved compounds, this did not interfere with the goal of assaying this sample for TRIG. In the other MDI-based samples, the monomer and only one other compound in the chromatogram were identified as containing isocyanate

There was a high degree of consistency in the ratio of detector responses used to identify TRIG compounds in the three MDI-based materials. MDI monomer standard showed a detector RF ratio of 9.9 for UV absorbance at 245 nm and 370 nm. The observed RF ratios of the TRIG compounds identified in the MDI-based materials ranged from 9.6 to 10.5 (97% to 106% of the MDI standard).

Quantitation of total TRIG in the MDI-based samples using the MDI-MAMA-urea standard at either UV wavelength produced results that were not statistically different in comparison to the reference titration assay. For the M20S sample, a recovery of 105% was seen for quantitation at 245 nm in comparison to the reference assay for TRIG; for quantitation at 370 nm, 99% recovery was observed. For the CMDI sample, including the unresolved compounds identified as peak 3, the respective recoveries were 105% and 104%; for the sample of PMMPI, recoveries of 95% and 96%, respectively, were obtained.

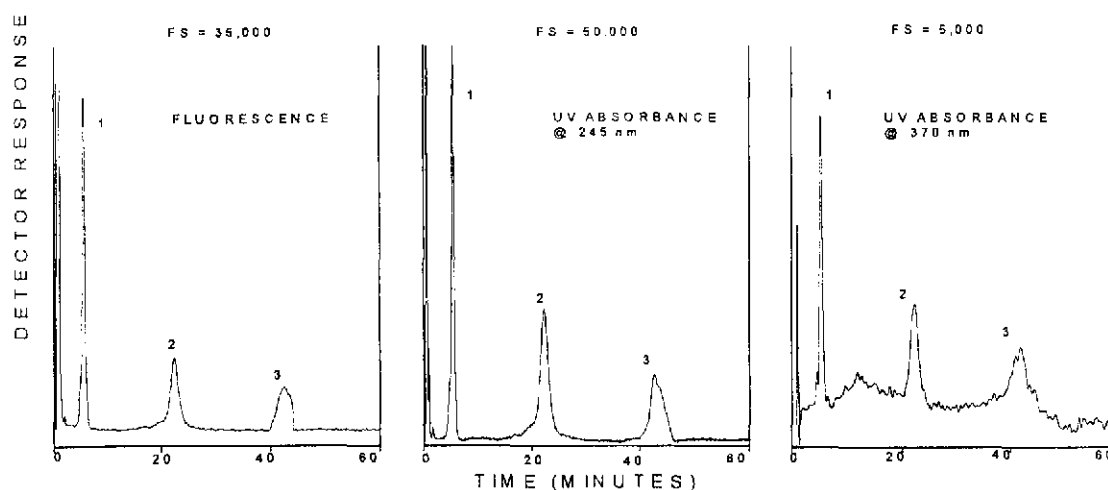


Figure 1: Chromatogram of a sample of MAMA-derivatized CMDI containing 100 μ mole TRIG per L.

TABLE 5
MAMA Assay of TRIG Content of MDI-Based Samples

Material	Peak No.	Detector Response Ratio (245 nm: 370 nm)	weight % TRIG		
			MAMA (245 nm)	MAMA (370 nm)	Reference Assay*
MDI monomer standard	1	$9.9 \pm 3.0\%$	---	---	---
	1	$9.9 \pm 10.0\%$	$18.1 \pm 8.9\%$	$17.2 \pm 6.4\%$	---
M20S	2	$10.5 \pm 2.9\%$	$4.9 \pm 1.8\%$	$4.5 \pm 4.9\%$	---
	total	---	$23.0 \pm 6.7\%$	$21.6 \pm 4.7\%$	$21.9 \pm 10.5\%$
CMDI	1	$9.6 \pm 2.1\%$	$7.2 \pm 2.9\%$	$7.2 \pm 4.2\%$	---
	2	$9.9 \pm 2.0\%$	$6.3 \pm 4.4\%$	$6.2 \pm 3.7\%$	---
	3	$9.7 \pm 2.1\%$	$10.6 \pm 4.1\%$	$10.6 \pm 5.9\%$	---
	total	---	$24.1 \pm 3.0\%$	$23.9 \pm 3.9\%$	$23.0 \pm 1.7\%$
PMPPi	1	$9.7 \pm 3.1\%$	$16.3 \pm 5.0\%$	$16.4 \pm 7.3\%$	---
	2	$9.6 \pm 2.1\%$	$5.7 \pm 1.6\%$	$5.8 \pm 2.0\%$	---
	total	---	$22.0 \pm 3.6\%$	$22.1 \pm 5.3\%$	$23.1 \pm 5.6\%$

* reference assay by titration with di-n-butylamine / HCl

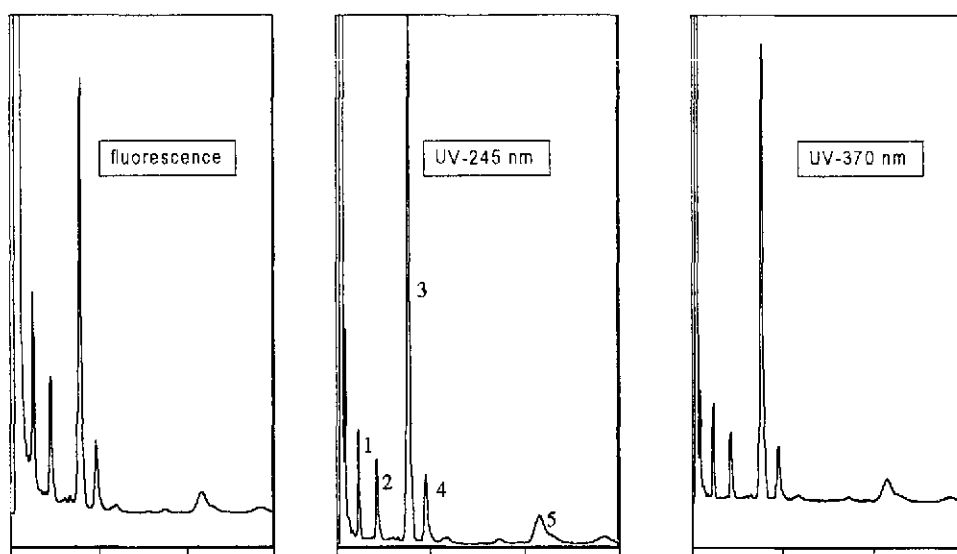
N.B.: all values are mean $\pm$ coefficient of variation

The data for the HDI-based materials is shown in Table 6, while Figure 2 presents a chromatogram of the Desmodur N100 sample. In this chromatogram, four peaks were identified as having contained isocyanate. Peak 1 was identified as HDI monomer and accounted for less than 5% of the total TRIG in this sample. In contrast, no HDI monomer was detected in the sample of Imron 192S. Peak 3 was presumed to be HDI-biuret since it was clearly the largest component of both samples. Peaks 2 and 4 were TRIG-containing compounds of unknown structure which were presumably other oligomeric forms of HDI. Peak 5 in the chromatogram was not considered to have contained isocyanate since its detector response ratio was 15.5, outside of the selection criteria. The detector response ratios of the four TRIG compounds identified in these samples ranged from 8.4 to 9.3, equivalent to a range of 101 to 112% of that of the HDI-monomer standard which had an average detector response ratio of 8.3.

Quantitation of total TRIG in the HDI-based samples yielded results that were not significantly different from that of the reference titration assay. For the Desmodur N100 sample, recoveries of 105% and 102% were obtained when quantitating TRIG by UV absorbance at 245 nm and 370 nm, respectively. For Imron 192S, these recoveries were 106% and 96%, respectively.

The Rextthane sample contained both 2,4-TDI and 2,6-TDI monomers as well as two other late-eluting compounds that contained isocyanate according to the selection criteria (Figure 3 and Table 7). The detector response ratios of these two peaks were 11.8 and 12.7, respectively, and were within the selection criteria of $\pm 20\%$ when compared to 2,4-TDI.

Quantitation of TRIG in the Rextthane sample yielded recoveries of 107% and 100% for UV absorbance at 245 nm and 370 nm, respectively, in comparison to the titration assay. The contribution of TRIG in this sample from the two TDI monomers amounted to approximately 55% of the total, with 2,6-TDI accounting for about three times as much TRIG as 2,4-TDI.



45-minute chromatographic runs

Figure 2: Chromatogram of a MAMA-derivatized sample of Desmodur N100 containing 98.7 μ mole TRIG per L.

TABLE 6
MAMA Assay of TRIG Content of HDI-Based Samples

Material	Peak No.	Detector Response Ratio (245 nm: 370 nm)	weight % TRIG		
			MAMA (245 nm)	MAMA (370 nm)	Reference Assay*
HDI monomer standard	1	$8.3 \pm 2.4\%$	---	---	---
Desmodur N100	1	$8.7 \pm 8.0\%$	$0.7 \pm 10.2\%$	$0.7 \pm 3.0\%$	---
	2	$8.9 \pm 3.4\%$	$0.7 \pm 1.0\%$	$0.7 \pm 2.5\%$	---
	3	$8.4 \pm 0\%$	$11.5 \pm 2.5\%$	$11.3 \pm 2.4\%$	---
	4	$9.3 \pm 3.2\%$	$1.8 \pm 2.4\%$	$1.6 \pm 2.7\%$	---
	5	$15.5 \pm 5.0\%$	0	0	---
	total	---	$14.7 \pm 2.5\%$	$14.3 \pm 4.4\%$	$14.0 \pm 10.0\%$
Imron 192S	1	none detected	---	---	---
	2	none detected	---	---	---
	3	$9.0 \pm 5.6\%$	$4.7 \pm 1.9\%$	$4.3 \pm 6.3\%$	---
	4	$8.9 \pm 5.6\%$	$0.6 \pm 6.6\%$	$0.6 \pm 8.9\%$	---
	total	---	$5.3 \pm 1.7\%$	$4.8 \pm 5.8\%$	$5.0 \pm 2.6\%$

* reference assay by titration with di-n-butylamine / HCl

N.B.: all values are mean $\pm$ coefficient of variation

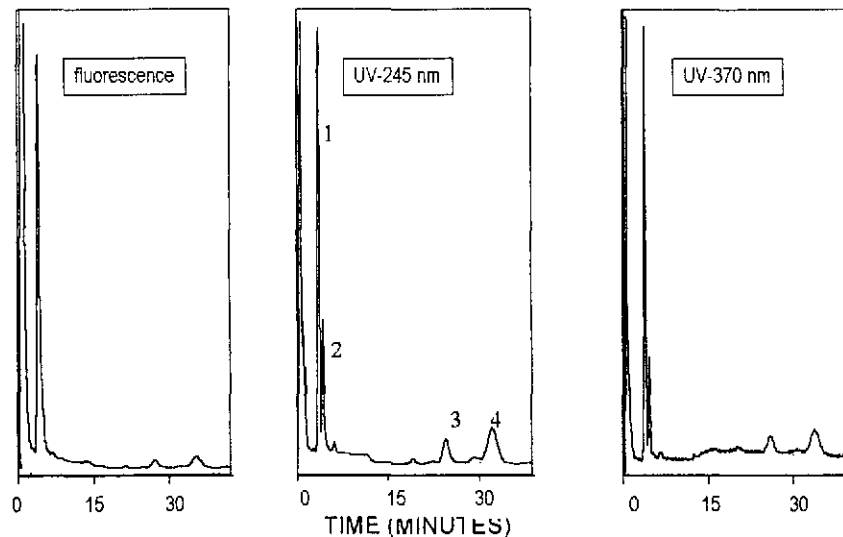


Figure 3: Chromatogram of a MAMA-derivatized sample of Rexthane containing 127 μmole TRIG per L.

TABLE 7
MAMA Assay of TRIG Content of a TDI-Based Sample

Material	Peak No.	Detector Response Ratio (245 nm: 370 nm)	weight % TRIG		
			MAMA (245 nm)	MAMA (370 nm)	Reference Assay*
2,6-TDI monomer standard	1	$9.8 \pm 6.1\%$	---	---	---
2,4-TDI monomer standard	2	$10.9 \pm 4.6\%$	---	---	---
Rexthane	1	$10.5 \pm 1.9\%$	$0.7 \pm 4.4\%$	$0.7 \pm 5.0\%$	---
	2	$12.6 \pm 9.5\%$	$0.2 \pm 5.2\%$	$0.2 \pm 7.7\%$	---
	3	$11.8 \pm 10.2\%$	$0.3 \pm 9.4\%$	$0.3 \pm 15.9\%$	---
	4	$12.7 \pm 6.3\%$	$0.5 \pm 7.8\%$	$0.5 \pm 16.1\%$	---
total		---	$1.7 \pm 7.5\%$	$1.6 \pm 5.9\%$	$1.6 \pm 1.9\%$

* reference assay by titration with di-n-butylamine / HCl

N.B.: all values are mean $\pm$ coefficient of variation

c. Assessment of Interference from Phosgene

Phosgene was evaluated as a possible interferant for the MAMA chemical labeling method. Phosgene gas was generated from a permeation device (VICI Metronics, Santa Clara, CA) housed in a standards generator (AID Model 360, Avondale, PA) held at a constant 30°C with a flow of 1.0 L/min of house air dried over silica gel. The output of the standards generator was further diluted with dried house air to yield a final test concentration of 100 ppb phosgene. To evaluate the potential interference, samples from this test atmosphere were collected in midjet impingers containing 10 mL of a solution of 0.1 mg MAMA / mL in acetonitrile at a flow rate of 1.0 L/min for 30 minutes. These samples were then analyzed by the same HPLC-UV-fluorescence technique that was applied to the TRIG compounds. For this procedure, HDI-MAMA-urea was used as the standard reference material.

A chromatogram showing the result of reacting MAMA reagent with phosgene gas is shown in Figure 4. A peak with a retention time approximately twice that of HDI-MAMA-urea (13 minutes in comparison to 6.5 minutes for HDI-MAMA-urea) was apparent. In addition to being fluorescent, this compound exhibited a UV absorbance detector ratio of 10.5 ± 0.9 which was within 1% of that for the HDI standards used for comparison. Peak 1 in the chromatogram therefore fell within the criteria for classification as an apparent source of TRIG. The other unmarked peaks in the chromatogram were also present in the reagent blank and represent excess MAMA reagent and unknown contaminants.

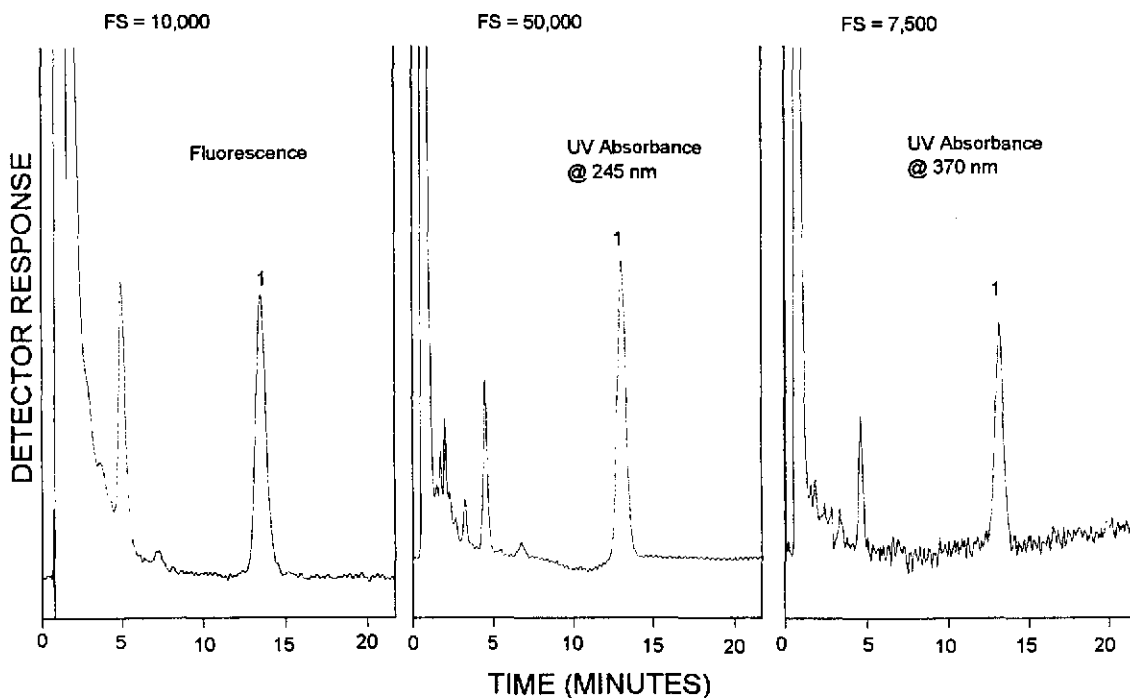
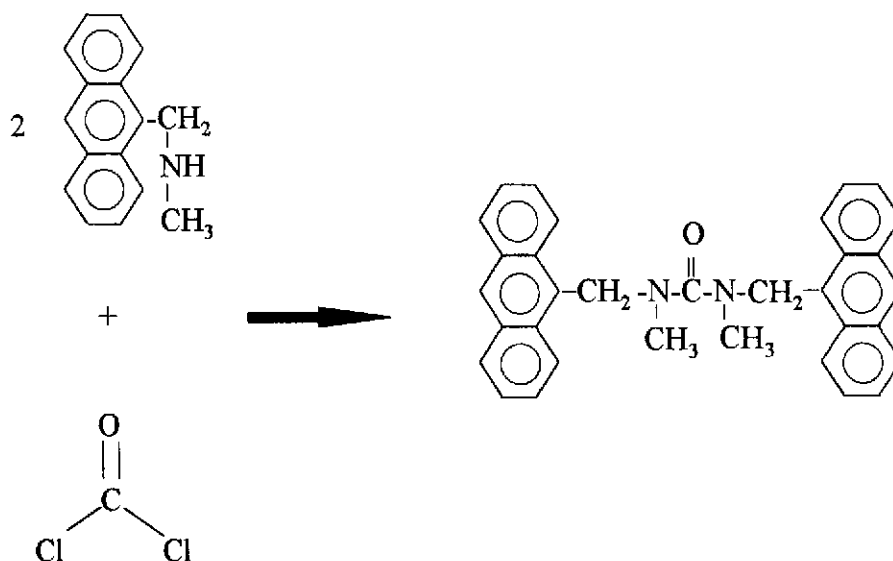


Figure 4: Chromatogram of a sample of MAMA reagent in acetonitrile reacted with phosgene gas.

In this experiment, the equivalent response of 100 ppb phosgene in comparison to HDI-MAMA-urea standards was found to be 239 ± 15 ppb TRIG. These results were in line with the expected reaction of phosgene with MAMA, from which phosgene should react with MAMA as two TRIG equivalents:



d. Development of the Dichotomous Sampler

- The Dichotomous Sampler

The dichotomous sampler was obtained from University Research Glassware (Model 2000, URG, Carrboro, North Carolina). The device consisted of an annular denuder in series with a size selective aerosol pre-separator (cyclone or impactor inlet) and an aerosol filter or impinger (Figure 5).

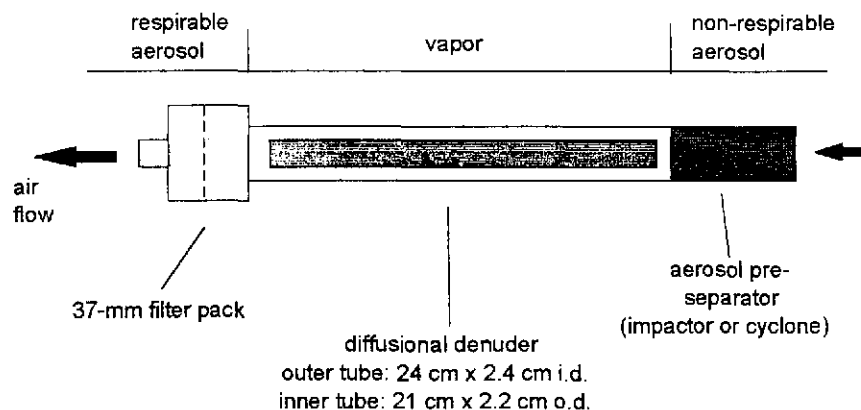


Figure 5: Dichotomous Trig - Aerosol / Vapor Sampler

All components were made of either borosilicate glass, Teflon, or stainless steel. The inlet to the denuder used one of two aerosol preseparators: an 11 mm - diameter glass tube which acted as an elutriator, followed by an acceleration jet and 1.1 cm diameter porous stainless steel impaction plate ($D_{50} = 2.5 \mu\text{m}$ at a sampling flow rate of 10 L/min); or an aluminum cyclone with a $D_{50} = 2.5 \mu\text{m}$ at a flow rate of 3 L/min. The preseparator was followed by the first annular denuder section, consisting of inner and outer glass cylinders with an annular spacing of 0.1 cm in between. The outer diameter of the denuder tube was 2.6 cm, and the length was 24 cm. Other sections of denuder tube were placed in series as desired, using specially designed couplings with Teflon coated O-rings. The final stage of the sampler was typically a 37 mm Teflon filter holder containing a treated glass fiber filter. For certain experimental runs, an impinger containing MAMA in acetonitrile or dimethylsulfoxide was used as the final stage in the dichotomous sampler. At a sampling flow rate of 10 L/min, the denuder has a predicted collection efficiency of 99.9% for gases of molecular weight less than 64.⁽⁴⁵⁾

The initial evaluations of the dichotomous sampler were performed with condensation aerosols of MDI. For this work, the Nitro Reagent method for MDI⁽⁴⁷⁾ was adapted to the dichotomous sampler. Subsequent phases of the project were concerned with adapting the MAMA reagent technique for use in the dichotomous sampler and evaluating its performance for various isocyanate monomers and oligomers.

- Measurement of MDI with Nitro Reagent - Dichotomous Sampler

For this initial work, the denuder walls and 37 mm glass fiber filter (Gelman Type AE) used as the dichotomous sampler backup were coated with Nitro Reagent (N-4-nitrobenzyl-N-1-propylamine) for collection and analytical derivatization of MDI as the Nitro Reagent urea.

Denuder sections were coated with Nitro Reagent by addition of 1 mL of a solution of 6.8 mg/mL, Nitro Reagent in hexane. The denuders were capped and the solution rolled around to evenly coat the denuder walls. The hexane was then evaporated with a nitrogen stream, leaving behind a coating of Nitro Reagent.

Glass fiber filters (Gelman type A/E) were coated by dipping in the hexane solution of Nitro Reagent and drying under nitrogen. Thirty-seven mm filters were used in the dichotomous sampler, while 13 mm filters were placed in polypropylene Swinney cassettes and used for collecting MDI according to the reference NIOSH technique.⁽⁴⁷⁾ The dichotomous samplers were operated at a flow of 10 L/min, while the 13 mm treated filters were used to collect MDI at a flow of 1 L/min. The flows of both sampling devices were controlled with critical orifices.

Controlled test atmospheres of MDI vapor and aerosol were generated in a dynamic flow chamber shown in Figure 6.^(48,49) The chamber was a horizontal laminar flow cabinet with dimensions of 2.4 m x 1.2 m x 1.8 m (8 ft. x 4 ft. x 6 ft) and was constructed from stainless steel and glass. Room air passed through charcoal and HEPA filters prior to entering the chamber. The dilution air was conditioned for temperature and humidity by the building's HVAC system. Dilution flow through the chamber was held at 8.05 m³/min (285 ft³/min) with a resulting flow velocity of about 3.7 m/min (12 ft/min). MDI was added to the chamber air at an engineered restriction which resulted in turbulence and thorough mixing of the contaminant with the dilution air prior to entering the laminar flow sampling zone in the chamber. MDI was generated by flash evaporation of a solution of 5 % MDI in acetone metered to a heated, nitrogen-flushed generator by a syringe pump. MDI for this work was obtained from BASF corporation, Geismar LA (Lupranate®M). The material was nominally 98% 4,4'-isomer with 2% of other isomers.

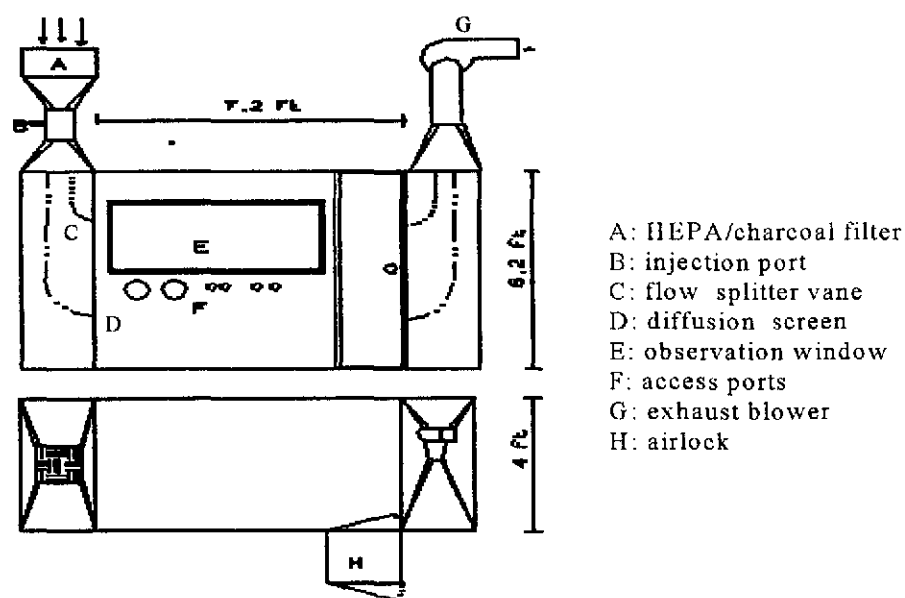


Figure 6: Schematic of laminar flow test chamber.

The concentration of MDI in the chamber was continuously monitored with a Model 7100 isocyanates monitor (MDA Scientific, Lincolnshire IL) and ranged from 24 to 355 $\mu\text{g}/\text{m}^3$ (2.3 to 34.7 ppb). Aerosol levels and size distribution were monitored in the test atmospheres with a Climet Model 7400 aerosol spectrometer (Climet Instruments Co., Redlands, CA) and a Sibata P5H dust monitor (MDA Scientific, Lincolnshire, IL). The condensation aerosols produced in the test atmospheres were sub-micron in size, with the average count median diameter being 0.36 μm (standard deviation of the mean equal to 0.06 μm), and the particle clouds were nearly monodisperse, the geometric standard deviations ranging from 1.26 to 1.65. Temperature and relative humidity of the test atmospheres ranged from 24.9°C to 27.2°C and 48% to 64%, respectively.

MDI-Nitro Reagent-urea derivative was recovered from the samplers by desorption with acetonitrile. The denuder sections were individually desorbed by addition of 2.0 mL of acetonitrile. After capping, the denuder was manually shaken for several minutes. The acetonitrile extract was then decanted into a sample vial and submitted for analysis. The filter samples were placed in extraction vials and desorbed with acetonitrile with sonication for 10 minutes. The 37 mm filters were desorbed with 10.0 mL of acetonitrile, while the 13 mm filters were treated with 1.0 mL. After desorption, the extracts were clarified by passing through a 0.45 μm pore size Nylon syringe filter (Alltech Associates, Deerfield IL).

Samples were analyzed by high performance liquid chromatography (HPLC). Detection was by ultraviolet absorbance using a Perkin Elmer Model LC90 UV detector set at 270 nm, and a Waters Model 440 detector set at 254 nm. Chromatography was done with a 4.6 mm x 5 cm column packed with 5 μm Supelcosil LC18DB (Supelco, Belafonte PA). The mobile phase consisted of 57 % acetonitrile, 43 % aqueous buffer (0.08 % triethylamine, 0.16 % H_3PO_4), pumped at a flow rate of 1.5 mL/min. Sample injection volumes were 20 μL . Quantitation was done at 270 nm in comparison to standards prepared from MDI - Nitro Reagent - urea that was synthesized and purified in the laboratory.

Table 8 summarizes the results from this phase of the project. The ratio of total MDI collected by dichotomous sampler to that of the reference sampler was 1.04 ± 0.09 (mean $\pm$ s.d.). When examined by paired t test, there was no significant difference between the dichotomous and reference samplers, $p = 0.11$.

TABLE 8
Experimental Evaluation of Dichotomous Nitro Reagent Sampler for MDI

MDI Collected ($\mu\text{g}/\text{m}^3$)					Relative Aerosol Level (cpm)
First Denuder ($\eta, \%$)*	Second Denuder	Backup Filter	Dichotomous Sampler Total	Reference Sampler Total	
---	---	---	---	---	15.2 <i>background</i>
28.0 (85.6)	4.7	ND	32.7	28.7	15.8
22.6 (90.4)	2.4	ND	25.0	23.6	16.5
32.6 (97.3)	0.9	ND	33.5	29.6	16.1
45.1 (93.4)	3.2	ND	48.3	50.0	16.1
35.7 (92.7)	2.8	ND	38.5	43.3	16.7
77.1 (91.6)	7.1	3.7	87.9	86.5	38.0
74.4 (94.8)	4.1	4.3	82.8	81.0	43.3
90.7 (94.2)	5.6	5.1	101.3	88.0	42.6
118.0 (97.0)	3.7	38.8	160.5	139.1	153.7
104.0 (95.4)	5.0	46.7	155.8	167.9	155.3
103.2 (92.1)	8.9	90.4	202.6	173.3	201.7
68.2 ---	79.0	125.0	272.1	270.8	529.1
108.4 (88.6)	14.0	151.1	273.3	275.7	497.3
137.4 (95.2)	7.0	125.1	269.6	276.5	547.3
88.0 (85.4)	15.0	280.7	383.6	353.9	562.0
83.6 (77.4)	24.4	238.8	346.9	355.2	436.6
98.5 (88.9)	12.3	278.1	389.0	343.2	454.7
paired t = 1.696 p = 0.11					

* η = collection efficiency for MDI vapor.

Background aerosol levels in the test atmosphere were constant at about 15 cpm up to an MDI concentration of approximately $75 \mu\text{g}/\text{m}^3$. As the concentration of MDI in the atmosphere increased beyond $75 \mu\text{g}/\text{m}^3$, the aerosol level also increased. The formation of condensation aerosol corresponded well with the expected saturation point of MDI at the experimental temperature which has been reported to be between approximately $55 \mu\text{g}/\text{m}^3$ and $100 \mu\text{g}/\text{m}^3$, depending on the ratio of 2,4'- and 4,4'- isomers.⁽²⁶⁾

The partitioning of MDI into vapor and aerosol was clearly reflected in the performance of the dichotomous sampler. Essentially all MDI collected by the sampler was found on the denuder sections up to a concentration of about $75 \mu\text{g}/\text{m}^3$. Beyond this point, breakthrough onto the backup filter was seen and correlated with the presence of aerosol. The amounts of MDI found on the denuders became relatively constant varying between 103.0 and $144.4 \mu\text{g}/\text{m}^3$, while that on the backup filter continued to rise as the overall concentration of MDI increased. This reflected the production of saturated atmospheres of MDI vapor which were collected by the denuders, with ever larger amounts of MDI aerosol penetrating the denuders and being collected on the backup filter. The pattern of breakthrough onto the backup filter corresponded closely to the pattern of aerosol buildup as a function of concentration.

From equations 1 - 4, collection efficiencies of MDI vapor and particulate were predicted for the URG denuder and the performance of the dichotomous sampler matched these theoretical predictions closely. A diffusion coefficient of $0.052 \text{ cm}^2/\text{sec}$ was first estimated for MDI using the method of Fuller, Schettler and Giddings.⁽⁵⁰⁾ For one length of denuder tube operated at a flow rate of $10 \text{ L}/\text{min}$, a collection efficiency of 94.1% was then predicted for MDI vapor, assuming the denuder wall acts as a perfect absorber. The collection efficiency of the denuder is simply the complement of the penetration efficiency:

$$\eta = 1 - P \quad 6$$

The first denuder in series collected $91.6 \pm 5.2\%$ of the vapor-phase MDI; i.e., the total amount of MDI collected by the two denuders in series. This mean was calculated without the run at $272 \mu\text{g}/\text{m}^3$ since more MDI was found on the second denuder than on the first, probably as a result of improper coating with Nitro Reagent.

For MDI particulate, diffusion coefficients for 1 and $0.1 \mu\text{m}$ AED particles are only $2.8 \times 10^{-7} \text{ cm}^2/\text{sec}$ and $6.8 \times 10^{-6} \text{ cm}^2/\text{sec}$, respectively. This results in exceedingly small values of μ' . Although the exact solution of the penetration equation for aerosols in the annular denuder is not available, comparison to the model for tubular denuders (equation 3), suggests that the penetration fraction for these size particles through the URG denuder is likely to be close to unity. Thus the nearly complete penetration of aerosol through the denuders was in line with expectations.

- Development of the MAMA Dichotomous Sampler

A series of laboratory investigations were carried out in order to adapt the MAMA reagent system to use in the dichotomous sampler and to optimize its performance for speciating vapor and aerosol forms of TRIG. Initial work was done with HDI which was chosen because of its

intermediate volatility and reactivity. For collection and speciation of HDI vapor by the dichotomous sampler, the following factors were evaluated: sampler flow rate (1, 2.8, 10 L/min), the amount of MAMA reagent coated on the dichotomous sampler stages (100 µg or 1 mg), incorporation of a non-volatile liquid in the coating (tributylphosphate), and treatment of the impactor stage with MAMA reagent. The results of these investigations are tabulated below.

Table 9
Initial Evaluations of MAMA Dichotomous Sampler for HDI Vapor

Experiment No.	Experimental Conditions	Distribution of Isocyanate - % of Total
1	HDI vapor; dichotomous sampler flow = 10 L/min; 100 µg MAMA per denuder; treated filter backup; Impactor uncoated.	filter 34 ± 22% denuder 2 23 ± 16% denuder 1 43 ± 15% impactor 0.6 ± 1.1%
2	HDI vapor; dichotomous sampler flow = 1 L/min; 100 µg MAMA per denuder; treated filter backup; impactor uncoated.	filter 58 ± 42% denuder 2 1.8 ± 3.6% denuder 1 41 ± 37% impactor 0.7 ± 1.1%
3	HDI vapor; dichot flow 2.8 L/min; 100 µg MAMA per denuder; impinger backup; impactor uncoated.	impinger 4.5 ± 5.0% denuder 2 31 ± 12% denuder 1 64 ± 8.1% impactor 0 ± 0%
4	HDI vapor; dichot flow = 2.8 L/min; 100 µg MAMA & 20 mg tributylphosphate per denuder; impinger backup; impactor uncoated.	impinger 0.7 ± 1.5% denuder 2 14 ± 10% denuder 1 85 ± 11% impactor 0.1 ± 0.2%
5	HDI vapor; dichot flow = 2.8 L/min; 1 mg MAMA per denuder; impinger backup; impactor coated.	impinger 0.7 ± 1.6% denuder 2 5.2 ± 4.9% denuder 1 70 ± 7.6% impactor 24 ± 7.5%
6	HDI vapor; dichot flow = 2.8 L/min; 1 mg MAMA & 20 mg tributyl-phosphate per denuder; impinger backup; impactor coated.	impinger 0 ± 0% denuder 2 2.9 ± 4.3% denuder 1 81 ± 11% impactor 16 ± 6.8%

Experiments 1 - 3 were carried out using test atmospheres produced in the laminar flow chamber. Nitrogen was bubbled through liquid HDI contained in a fritted glass VOA bubbler (Ace Glass). The HDI-laden nitrogen was then passed through a glass fiber filter prior to being injected into the chamber. The concentration of HDI vapor during these tests ranged from 67

to 302 ppb. In each run, two denuder sections were used in series. They were coated with 100 µg MAMA reagent by adding the appropriate amount of MAMA in hexane to the denuder, and evaporating the hexane under a flow of nitrogen as described previously for coating with Nitro Reagent. The backup filter in experiments 1 and 2 was coated with MAMA by dipping in the MAMA / hexane solution and evaporating off the hexane under a nitrogen flow. Using this procedure, the filters were coated with approximately 200 µg of MAMA. In experiment 3, the backup impinger contained 10 mL of a solution of 100 µg/mL MAMA in acetonitrile. After sample collection, each component of the dichotomous sampler was desorbed/treated and analyzed by HPLC: the impactor plates were removed immediately after sampling and placed into 1 mL of the MAMA/acetonitrile solution; the denuders were desorbed with 2.0 mL acetonitrile; the treated filter was desorbed in 1.0 mL of acetonitrile and passed through a syringe filter prior to analysis; the impinger sample solution was analyzed directly. For each sampling run, a reference sample was collected using the Nitro Reagent technique with HPLC analysis. ⁽⁴⁷⁾

The results of the correlation of the dichotomous sampler and Nitro Reagent reference are shown in Figure 7. Overall, the concentrations of total HDI as determined by the dichotomous sampler correlated very well with those determined by the Nitro reagent reference technique. Linear regression of the results (dichotomous sampler = dependent variable; Nitro reagent sampler = independent variable) yielded a slope of only 1.03, near unity, and an intercept of 3.4 ppb.

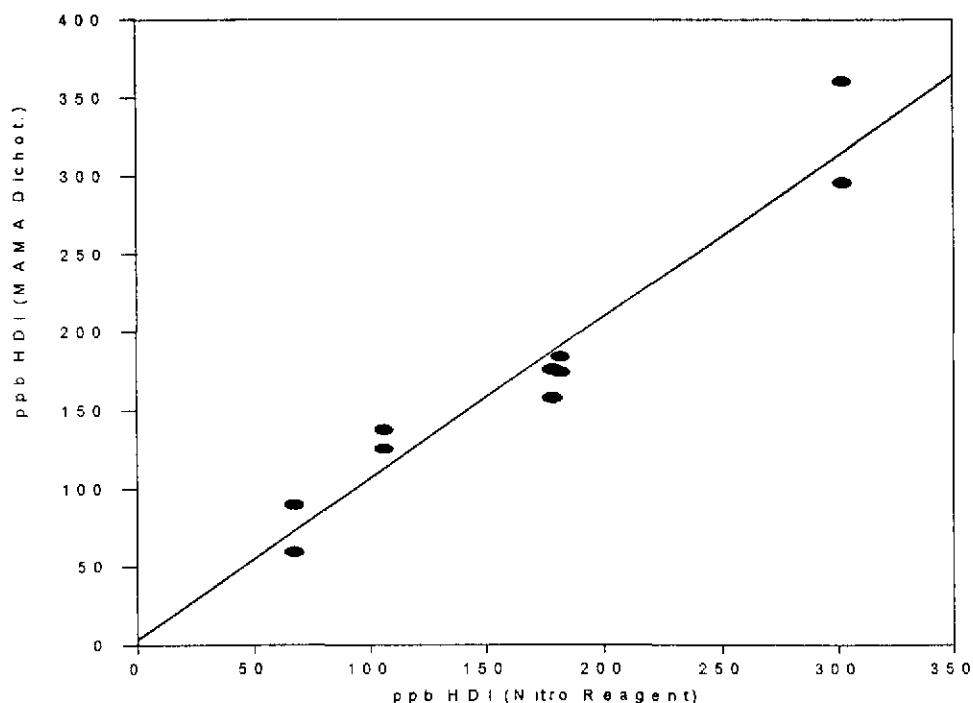


Figure 7: Dichotomous Sampler vs. Nitro Reagent Filter Technique for HDI Vapor

Insignificant amounts of HDI were found on the uncoated impactor plate. However, penetration of HDI past the denuders and onto the backup filter or impinger was significant, ranging up to 58% of the total. In addition, relatively large amounts of HDI penetrated past the

first denuder to be partially collected by the second denuder in series. There was no clear effect of flow rate on the collection efficiencies of the sampler components. Review of these results suggested that modifications to the sampler design were needed to improve its performance in separating vapor phase HDI, which should be distributed only on the denuder sections, from aerosolized HDI.

Experiments 4 through 6 were conducted with a bench top system for generating test atmospheres which is shown schematically in Figure 8. HDI vapor was generated using a silicone rubber permeation tube.⁽⁵¹⁾ Dry air was passed over the permeation tube which was held at a constant temperature, and subsequently diluted with room air, resulting in test atmospheres containing 75 ± 10 ppb of HDI. In these experiments, the sampler flow was held constant at 2.8 L/min. The denuders were prepared for sampling in the following ways: coated with 100 μ g MAMA and 20 mg tributylphosphate (TBP); coated with 1 mg MAMA; coated with 1 mg MAMA and 20 mg TBP. TBP is a non-volatile, viscous liquid which was added in an effort to improve the collection of HDI vapor. TBP is transparent under the HPLC detection conditions used for MAMA-derivatized isocyanate sample analysis and thus does not interfere with the method. Also, the impactor plate was coated with derivatizing agent in experiments 5 and 6 for comparison to collection by the uncoated plate.

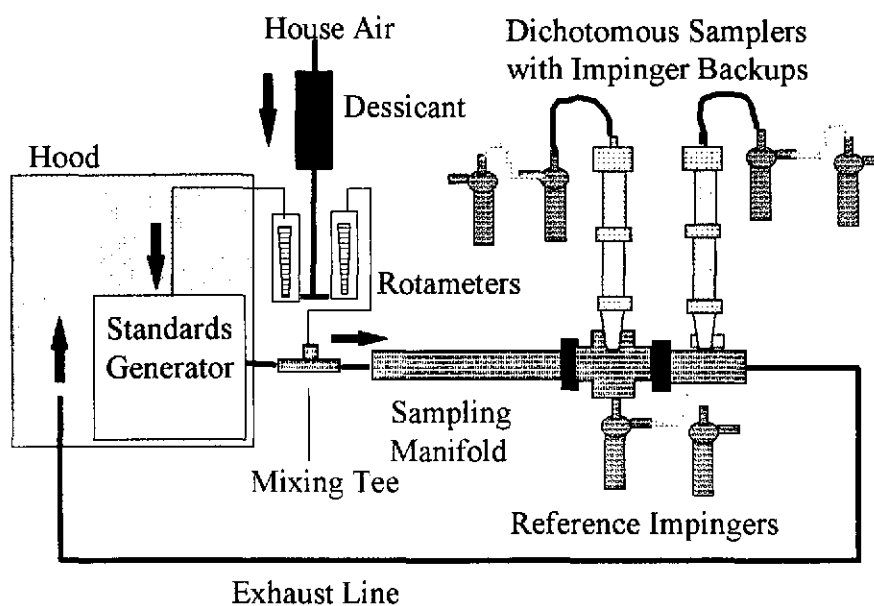


Figure 8: Benchtop system for producing test atmospheres of vapor phase isocyanates

The collection efficiency of the denuders was improved both by inclusion of TBP and by increasing the amount of MAMA reagent. It is apparent that a coating of 100 μ g MAMA alone is insufficient for efficient collection of HDI vapor. However a coating of 1 mg MAMA without TBP appeared adequate. A further slight improvement in collection was noted with the inclusion of tributylphosphate in the 1 mg MAMA coating. A dramatic improvement in collection was noted when TBP was added to the 100 μ g MAMA coating.

Significant collection of HDI vapor was seen when the impactor stage was also coated with reagent. Collection of vapor phase isocyanate on the impactor would negate using the dichotomous sampler to speciate HDI into vapor and aerosol phases. Overall then, these experiments indicated that the dichotomous sampler's denuders sections should be coated with 1 mg MAMA and 20 mg TBP, whereas the impactor plate should be left uncoated. Under these conditions, the impactor plate would have to be desorbed with a MAMA solution as soon after sample collection as is feasible. The data also suggest that impinger and treated filter backups are equally efficient at collecting any HDI which penetrates past the denuders.

The dichotomous sampler was next evaluated for collection of nine of the other ten isocyanate monomers: MIC, BUT, PIC, BEN, OTOL, PTOL, 2,4-TDI, 2,6-TDI, and HMDI. Test atmospheres of MIC were generated in the laminar flow chamber by metering liquid MIC into an evaporator by syringe pump. The evaporator was continuously flushed with room temperature nitrogen which was then fed into the chamber. The test atmospheres in these studies ranged between 5 and 10 ppb MIC. Dichotomous samplers using denuders coated with 1 mg MAMA and with and without TBP were evaluated. In all runs, the impactor plate was also coated and an impinger containing 10 mL of 0.1 mg/mL of MAMA in acetonitrile was used as the sampler backup. The dichotomous samplers were operated at a flow of 2.8 L/min for this work.

The isocyanates BUT, BEN, PIC, OTOL and PTOL were generated and sampled simultaneously. A cocktail made up of equal parts of each of these isocyanates was metered into the evaporator by syringe pump and then carried into the laminar flow chamber using nitrogen. The resulting concentrations of the isocyanates ranged as follows: 11 - 13 ppb BUT, 11 -13 ppb BEN, 8 - 10 ppb PIC, 8 - 10 ppb OTOL, and 9 -11 ppb PTOL. For these sampling runs, the dichotomous sampler used a coated impactor plate and denuder sections coated with 1 mg MAMA and TBP. Impingers containing MAMA solution were used as backups to the dichotomous sampler which was operated at flow rates of 2.8 L/min.

Collection of 2,4-TDI and HMDI by the dichotomous sampler were evaluated together. A 1:1 cocktail of 2,4-TDI and HMDI was diluted to a level of 5% v/v with acetone and then metered into the evaporator via syringe pump. The evaporated isocyanates were carried into the laminar flow chamber by nitrogen flow. The sample runs ranged in concentration from 20 to 60 ppb of 2,4-TDI and from 20 to 40 ppb of HMDI. The dichotomous sampler was setup and operated as just described.

Test atmospheres of 2,6-TDI were prepared in the bench-top flow through system. Vapors of 2,6-TDI were generated by silicone rubber permeation tube under dry air and diluted with room air in the sampling manifold. The concentration of 2,6-TDI during the test runs ranged from 10 to 20 ppb. The dichotomous samplers used denuders coated with and without TBP along with 1 mg MAMA. The impactor plates were coated with reagent and impinger backups were utilized.

Table 10
Evaluation of MAMA Dichotomous Sampler for Collection of Nine Isocyanate Monomers

Isocyanate Tested	<u>Impactor</u> % of Total Isocyanate Collected	<u>First Denuder</u> % of Total Isocyanate Collected (*)	<u>Second Denuder</u> % of Total Isocyanate Collected	<u>Backup Impinger</u> % of Total Isocyanate Collected
MIC (w/o TBP)	4.2 ± 3.2	9.2 ± 2.8 (9.6%)	9.6 ± 7.0	76.3 ± 11.3
MIC (with TBP)	5.7 ± 3.8	27.0 ± 8.4 (28.6%)	23.1 ± 5.2	44.3 ± 8.1
BUT	5.6 ± 1.2	86.1 ± 4.5 (91.2%)	7.7 ± 3.6	0 ± 0
BEN	5.6 ± 0.6	88.9 ± 3.4 (94.2%)	5.5 ± 3.0	0 ± 0
PIC	27.6 ± 1.8	72.3 ± 2.0 (100%)	0 ± 0	0 ± 0
OTOL	25.0 ± 1.1	68.8 ± 3.9 (91.7%)	6.3 ± 3.5	0 ± 0
PTOL	29.1 ± 3.2	67.0 ± 5.1 (94.4%)	4.0 ± 6.1	0 ± 0
2,4-TDI	21.0 ± 1.7	78.5 ± 1.4 (99.4%)	0.3 ± 0.4	0.2 ± 0.3
HMDI	12.0 ± 1.6	88.0 ± 1.6 (100%)	0 ± 0	0 ± 0
2,6-TDI (w/o TBP)	20.0 ± 5.2	73.6 ± 6.2 (92%)	6.2 ± 3.0	0.2 ± 0.3
2,6-TDI (with TBP)	26.4 ± 4.2	71.4 ± 4.9 (95.6%)	2.2 ± 3.0	0 ± 0

* percentage collection efficiency for isocyanate penetrating past the impactor inlet.

MIC is the most volatile isocyanate investigated in this study (vapor pressure = 348 mm Hg at room temperature). MIC vapor was inefficiently collected by the dichotomous sampler, although a clear improvement was noted with the inclusion of TBP in the reagent coating. Even with TBP added, 44% of MIC penetrated to the dichotomous sampler backup. Without further modification to improve the collection efficiency, the dichotomous sampler would not be a reliable device for speciating MIC in the atmosphere.

For all the other isocyanate monomers, collection by the dichotomous sampler was complete with at most 0.2% of the total isocyanate breaking through to the backup impinger. Further, in all cases, one section of denuder was nearly perfect at collecting the vapor phase isocyanate penetrating past the coated impactor plate. This value ranged from a low of 91.2% for BUT (the most volatile of the isocyanates after MIC) to a high of 100% for HMDI (the least volatile of this group of isocyanates). A slight improvement in collection efficiency was also noted with inclusion of TBP in the reagent coating when sampling 2,6-TDI.

Again, significant collection of isocyanate vapor was seen on the coated impactor. These results suggest that for representative speciation of TRIG into vapor and aerosol fractions, the impactor should be uncoated during sampling. Immediately after sampling, the impactor could be removed and treated with derivatizing agent for subsequent measurement of TRIG in the non-respirable aerosol phase.

- Dichotomous Sampling of Oligomeric Isocyanate Mixtures

Evaluation of the dichotomous sampler for measurement and speciation of oligomeric isocyanate mixtures was performed using an aerosol test chamber. A schematic of the chamber is shown in Figure 9. The chamber is a laminar flow cabinet which operates under positive pressure by dilution air forced into the top of the unit by a fan. The cross section of the chamber is 1 ft². The fan moves air through the chamber at approximately 100 cfm, resulting in an average flow velocity of about 100 ft/min. Aerosol was generated using a Devilbiss Model 40 glass nebulizer. The aerosol and dilution air were mixed by passing through a series of perforated plate diffusers. The aerosol atmosphere then passed through a honeycomb flow straightener before entering the sampling zone of the chamber. The chamber was placed in a walk-in laboratory fume hood during use.

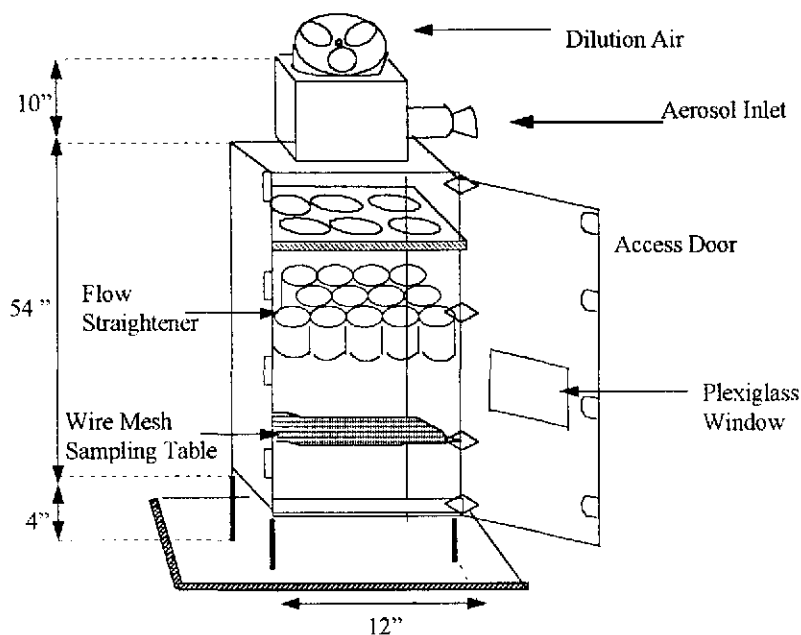


Figure 9: Schematic diagram of the isocyanate aerosol test chamber.

Testing of the dichotomous sampler with atmospheres of aerosolized Desmodur N100 (HDI-biuret) and CMDI (poly-methylene-poly-phenyleneisocyanate) was performed. Test atmospheres of Desmodur N100 were generated by nebulizing a solution of 1% Desmodur N100 in dimethylsulfoxide (DMSO). The nebulizer was operated at a flow rate of 14 L/min using compressed air. Initial work with the dichotomous sampler used an impactor inlet and the device was evaluated at sampling flow rates of 1 L/min, 2.8 L/min and 10 L/min. At 10 L/min, the D₅₀ of the impactor is 2.5 µm, while at 1 L/min it is estimated to be 4.8 µm. During

these initial evaluations, the denuders were coated with 100 µg MAMA reagent and the impactor plates were left uncoated but were desorbed with MAMA solution immediately after sample collection.

Table 11
Laboratory Evaluation of MAMA Dichotomous Sampler for Aerosolized Desmodur N100

Dichotomous Sampler Flow Rate	IMPACTOR	DENUDER	BACKUP
	% of TRIG Collected % of Total HDI Collected	% of TRIG Collected % of Total HDI Collected	% of TRIG Collected % of Total HDI Collected
1 L/min (n = 4)	48.4 ± 18.1	0 ± 0	51.6 ± 18.1
	20.8 ± 13.2	57.7 ± 11.0	21.6 ± 4.3
2.8 L/min (n = 8)	44.6 ± 12.7	0 ± 0	55.4 ± 12.7
	ND	ND	ND
10 L/min (n = 4)	84.3 ± 25.2	0 ± 0	15.7 ± 25.2
	14.2 ± 21.3	64.0 ± 9.6	21.9 ± 16.3

Desmodur N100 is primarily HDI-biuret, a trimer of HDI. The material contains a small amount of HDI monomer, which may reach a maximum of about 1.6% after long term storage. Our assay of this material, described in Table 6 yielded 0.7% HDI monomer as measured on the basis of TRIG equivalents. Approximately 80% of the TRIG in this material originates from the HDI-biuret. These initial evaluations of the dichotomous sampler for collection of Desmodur N100 shown in Table 10, clearly illustrated the separation of HDI-biuret, which should be found essentially only in the condensed phase, from the semi-volatile HDI monomer. No HDI-biuret was found on any denuder sections. The amount of HDI-biuret collected by the impactor inlet increased by almost a factor of two in going from a flow rate of 1 or 2.8 L/min to 10 L/min, reflecting the increased collection efficiency and decreased D_{50} of the impactor for higher flow rates. Interestingly, the HDI monomer was distributed over all three collection stages of the dichotomous sampler, although most was found on the denuder sections which should trap only vapor phase HDI. The amount of HDI found in the backup may not be accurately reflective of the amount associated with non-respirable or larger aerosols because of the use of only 100 µg MAMA on the denuders in this early work. As previously noted, poorer collection efficiency for the denuders was found with a lower loading of MAMA reagent on the denuders. Nonetheless, the impactor plates were uncoated and collected a significant amount of HDI monomer, indicating that the material was probably partitioning between the vapor and aerosol phases in these experiments.

In order to extend the application of the dichotomous sample to atmospheres containing very high loadings of aerosol, a cyclone inlet was investigated as a replacement for the impactor. The cyclone inlet (URG, Carrboro, NC) was designed with a D_{50} of 2.5 µm at a flow rate of 3 L/min. The dichotomous sampler with cyclone inlet was evaluated using the aerosol test chamber as described above. The test atmosphere was generated by nebulizing a solution of 1% Desmodur N100, 0.02% HDI in DMSO. HDI monomer was added to the mixture to increase its concentration in the test atmosphere and allow a more accurate assessment of its collection on the various stages of the dichotomous sampler. The denuders in this work were coated with 1 mg MAMA and 20 mg TBP. The dichotomous samplers were operated at a flow

rate of 2.8 L/min. Immediately after sampling, the cyclones were washed with a MAMA solution for measurement of collected isocyanate.

Table 12
Laboratory Evaluation of Dichotomous Sampler with Cyclone Inlet for Aerosolized Desmodur N100 Spiked with HDI Monomer

n = 6	% of Total HDI Collected	% of Total TRIG Collected
cyclone	13.5 ± 2.1	26.7 ± 6.9
diffusional denuder	78.3 ± 7.6	0 ± 0
backup filter	8.3 ± 6.3	73.3 ± 15.2

The concentrations of HDI and TRIG in these tests averaged 203 $\mu\text{g}/\text{m}^3$ (30 ppb) and 305 $\mu\text{g}/\text{m}^3$, respectively, with the latter reported as isocyanate group and not including HDI monomer. In these tests, no HDI-biuret or other oligomers of HDI was found on the denuder sections, indicating that these materials were completely in the condensed phase. In line with previous results, HDI monomer was distributed across the stages of the dichotomous sampler with most of the material being found on the denuders. This supports the theory that under the conditions of spray aerosolization, HDI tends to partition between vapor and condensed phases, even when the vapor concentration is about three orders of magnitude lower than its saturated vapor pressure.

The dichotomous sampler was next evaluated using test atmospheres of CMDI aerosol and vapor. These tests were again performed using the laminar flow aerosol chamber (Figure 9). CMDI was generated using the Devilbiss Model 40 nebulizer charged with a solution of 5 % CMDI in methoxyethyl acetate. The dichotomous sampler utilized the cyclone inlet and was operated at a flow rate of 2.8 L/min. The denuders were coated with 1 mg MAMA and 20 mg TBP. A treated glass fiber filter was used as the backup.

Table 13
Laboratory Evaluation of MAMA Dichotomous Sampler for Aerosolized CMDI

n = 6	% of Total MDI Collected	% of Total TRIG Collected
cyclone	50.2 ± 10.3	57.8 ± 11.3
denuders	28.1 ± 11.6	18.6 ± 9.6
backup filter	22.0 ± 8.1	23.5 ± 11.9

Our initial assay of CMDI (Table 5) showed that this material contained about 21% MDI by weight (~ 7% in TRIG equivalents). This represented about one-third of the total TRIG contained in the material. The concentrations of MDI and of TRIG (not including MDI) in the test atmospheres during the evaluations averaged $277 \pm 49 \mu\text{g}/\text{m}^3$ and $432 \pm 85 \mu\text{g}/\text{m}^3$, respectively. For MDI at the average test temperature of $27.3 \pm 0.4^\circ\text{C}$, the saturated vapor pressure is about $90 \mu\text{g}/\text{m}^3$.⁽²⁶⁾ The data indicate that on average, 28.1% of the MDI was found on the denuders, indicative of vapor phase material. This is equivalent to an average vapor concentration of $78 \mu\text{g}/\text{m}^3$ which is within 15% of the saturated vapor concentration at the test temperature. TRIG was distributed similarly to the MDI, with 18.6% (about $80 \mu\text{g}/\text{m}^3$ on

average) being found on the denuders. The TRIG on the denuders was completely attributed to one unidentified peak in the chromatograms. It is uncertain what the identity of the compound was; however, it would appear to have a vapor pressure similar to MDI if it is assumed that the denuders were capturing the fraction of the material present in the vapor phase.

e. Field Sampling in the Workplace

Field testing of the dichotomous sampler was conducted in two workplaces: a paint spray booth at a military facility which was being used to spray-paint vehicles with an HDI-based polyurethane paint; and a flexible polyurethane foam manufacturing plant which used TDI and MDI in the process.

- Field Sampling in the Polyurethane Paint Spray Booth

Sampling was conducted during the spray painting of a four-wheeled ammunition carrier. The painting was done in a paint booth which was 24 ft deep, 14 ft wide, and 13 ft high. The back wall of the booth was a filter plenum through which air was being exhausted at 69,000 ft³/min. A mixing / clean-up station was positioned inside the booth along one of the side walls. The spray painter was equipped with a Tyvek supplied air painting hood and Tyvek overalls during all mixing, painting, and clean-up operations. The vehicle was painted with Deft Green 24052 polyurethane (Deft Chemical Coatings, Irvine, CA). This is a two component paint based on HDI. The isocyanate catalyst component is a mixture of 0.15% HDI, 29.8% HDI-biuret in a mixture of toluene, xylene, 2-butanone, and ethoxyethyl acetate. The base component is a proprietary mixture of polyol, lead chromate, 2-butanone, ethoxyethyl acetate, and ethyl acetate.

Sampling was conducted separately during the mixing, painting, and clean-up phases of the process. Samples collected during paint mixing were stationed adjacent to and down wind from the mixing counter. During painting, samples were stationed directly in front of the filter plenum. Samples were positioned in both locations during the clean-up activity. In all cases, the dichotomous samplers were placed on tripods with the sampler inlets positioned about 3.5 to 4 ft above the floor. Dichotomous samplers with uncoated impactor inlets and with cyclone inlets were utilized. Because of the large loading of aerosol expected, only samplers with cyclone inlets were used during the painting cycle. Samplers with impactor inlets were used during mixing and clean-up. In all cases, one section of denuder tube was used which was coated with 1 mg MAMA and 20 mg TBP. Backups in all cases were glass fiber filters treated with the MAMA/TBP coating solution. All samples were collected at a flow rate of 2.8 L/min. Immediately after sample collection, the impactor plate or cyclone was desorbed with a solution of MAMA reagent in dioxane.

A representative chromatogram from a cyclone sample is shown in Figure 10. A single major peak corresponding to HDI-biuret is evident at a retention time of approximately 36 minutes. A second smaller peak representing about 4% of the TRIG content of the sample is evident at about 14 minutes. A trace of HDI monomer is seen at a retention time of 10.5 minutes. Seven other trace-level peaks were identified in this chromatogram as having contained TRIG using a

selection criteria of being within 20% of the detector ratio (absorbance at 245 nm : absorbance at 370 nm) observed for the HDI monomer standards. Further confirmation was provided by fluorescence detection. Quantitation of these peaks was done in comparison to HDI-MAMA-urea standards with detection by absorbance at 370 nm.

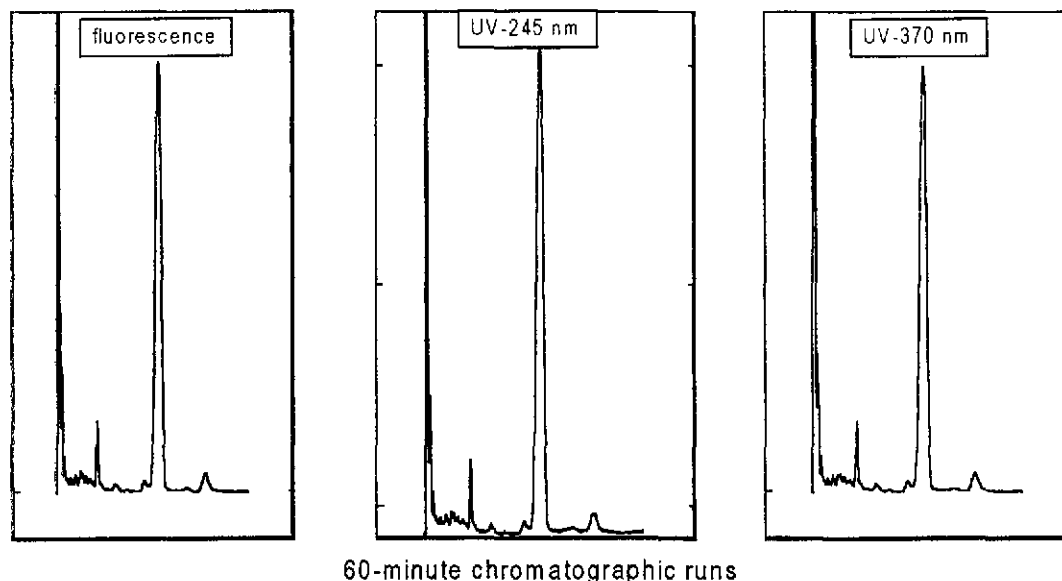


Figure 10: Chromatogram of a MAMA-derivatized cyclone inlet sample collected from a polyurethane paint overspray atmosphere.

No isocyanate was detected during the mixing operations. During painting, very high concentrations of aerosolized TRIG were measured, ranging from 199 to 551 $\mu\text{g}/\text{m}^3$. Most of this material was identified as HDI-biuret during chromatographic analysis. Small amounts of HDI monomer ranging from 7 to 20 $\mu\text{g}/\text{m}^3$ (1 to 2.9 ppb) were measured during the painting operation. In one pair of samples, there was evidence of HDI partitioning between vapor and aerosol phases, with 15 to 26% of the measured HDI being found in the cyclone or on the backup filter. In the other sample pair, all of the measured HDI was collected on the denuder. All of the non-HDI TRIG was collected on the cyclone and backup filter, indicating complete separation of these compounds into the aerosol phase of the paint overspray. During the clean-up operation, only small amounts of HDI were measured and these were completely in the vapor phase (on the denuder). No non-HDI TRIG was detected during clean-up.

Table 14
Results of Dichotomous Sampling for Aerosols and Vapor of HDI/TRIG During Spray
Application of Polyurethane Paint

AIR SAMPLE VOLUME (Liters)	VAPOR PHASE CONCENTRATION ($\mu\text{g}/\text{M}^3$)		AEROSOL PHASE CONCENTRATION ($\mu\text{g}/\text{M}^3$)		ACTIVITY
	HDI	*TRIG	HDI	*TRIG	
20	ND	ND	ND	ND	MIXING
20	ND	ND	ND	ND	MIXING
150	17	ND	3	551	PAINTING
150	14	ND	5	461	PAINTING
150	7	ND	ND	199	PAINTING
150	10	ND	ND	343	PAINTING
68	2	ND	ND	ND	CLEANUP/DRYING
68	5	ND	ND	ND	CLEANUP/DRYING
37	ND	ND	ND	ND	CLEANUP/DRYING
37	ND	ND	ND	ND	CLEANUP/DRYING

* TRIG: total reactive isocyanate group, reported as equivalent mass of isocyanate (e.g., there are 0.25 μg TRIG per μg HDI). Includes HDI-biuret, other HDI-oligomers, and polyurethane pre-polymers with free isocyanate. Does not include HDI monomer.

ND: not detected (LOD is approximately 0.1 μg HDI / TRIG per sample)

- Field Sampling in a Flexible Polyurethane Foam Production Plant

Field sampling with the dichotomous sampler was conducted at a factory manufacturing flexible polyurethane foam for use in carpet underpadding, mattresses, air filters, etc. The factory utilized three continuous production lines producing foam bats of various dimensions and formulations. Foams based on polyether and polyester polyols were made. Foams were formulated with TDI alone and with a mixture of TDI and MDI. Various finishing operations were carried out on produced foam, including reticulation operations, laminating operations, impregnation, and cutting and sizing.

Samples were collected in the following areas: Maxfoam production line, CTM/LFM production line, zapping operation and flame laminating operation. The maxfoam line produced a continuous foam bat produced using both TDI and TDI/MDI mixtures. The two components of the foam were mixed in a mixing head and then continuously poured out onto a moving film of

Kraft paper or polyethylene film. The rising foam bat then proceeded into a curing oven which was exhausted outside the building. After exiting the curing oven, the liner was mechanically removed from the foam, the foam was cut into bats and the bats were removed to a cooling/storage area. The CTM/LFM line was similar but produced a smaller cross-section foam bat and used only TDI in the formulations. For both of these lines, samples were collected next to the paper peeler at the end of the line. The paper peeler removed the Kraft paper or polyethylene film which was laid down on the line's conveyor belt and onto which the foam mixture was poured.

The zipper was a reticulation operation in which a foam bat was placed in a pressurized vessel containing a hydrogen/air atmosphere. Upon ignition, the explosive shock wave opened up the foam cells. The high temperature generated in the zipper cell can regenerate isocyanate from cured foam which may escape into the local workplace atmosphere when the foam is removed. The zipper cell was exhausted with air prior to opening in order to minimize the release of fumes from the zapped foam bat. Zapping was a batch operation done on a few foam bats at a time. Samples were collected near the operator's station which was just outside the access door to the zipper cell and enclosed within a vinyl strip curtain.

The flame laminator was a process in which two thin foam sheets were welded to one another by melting the foam at the interface of the sheets. The heat was supplied by a horizontal natural gas burner over which the foam sheets continuously passed. Immediately after passing over the burner, the foam sheets were joined and the cooling foam formed an adhesive bond between the two. Copious amounts of smoke and fume were released at the point of burning from the foam sheets. A large canopy hood was positioned above the laminator to extract these fumes. Samples were collected near the outside edge of the laminator, several feet above and away from the end of the gas burner.

For this work, the dichotomous samplers were set up with cyclone inlets, two sections of denuder tube, and backup glass fiber filters. The denuders and backup filters were coated with MAMA/TBP mixture. Samples were collected at 2.8 L/min. Each dichotomous sampler was paired with a 13 mm Nitro Reagent-coated filter for comparison testing. Nitro Reagent filter samples were collected at a flow rate of 1 L/min. The two sampler units were positioned side by side on a sampling tripod with their respective inlets positioned about 4 ft above the floor. After sample collection, the cyclone inlets were desorbed with a solution of MAMA in dioxane. The denuder sections, backup filter, and reference Nitro Reagent filter were sealed up and brought back to the laboratory for sample preparation and analysis by HPLC.

A summary of the results of the sampling in the foam plant is presented in Table 14. No MDI was detected in any of the samples. TDI ranged from non-detectable up to $129.4 \mu\text{g}/\text{m}^3$ (~18 ppb). Most of the TDI was the 2,6-isomer. Comparing the results of the dichotomous sampler to those of the Nitro Reagent sampler, a good correlation was obtained. Disregarding sample 9 which was contaminated when the edge of a foam bat sloughed off and fell on the sampling train, paired t tests of dichotomous sampler vs. Nitro Reagent sampler for the 2 isomers of TDI yielded the following results:

- 2,4-TDI: $t = 0.388$, $p = 0.71$
- 2,6-TDI: $t = 0.807$, $p = 0.44$

Thus no statistically significant difference between the two sampling devices was noted. In addition to the isomers of TDI and MDI, TRIG was also measured in the dichotomous samplers. TRIG compounds were identified in the chromatograms by ratio of UV absorbance at 245 nm to that at 370 nm in comparison to standards made from 2,4- and 2,6-TDI-MAMA-urea. The selection criteria were a detector ratio within 20% of that of the TDI standards and in addition, significant fluorescence. Small amounts of material classified as TRIG were noted in 8 out of 10 samples. In general, these compounds appeared in the chromatograms before the isomers of TDI which would suggest that they were lower molecular weight or higher polarity compounds, perhaps other isocyanate monomers or partially reacted TDI. Of course, a similar type of analysis could not be done with the Nitro Reagent samples which were only able to identify the diisocyanate monomers themselves.

Table 15
Summary of Results for Isocyanate Sampling / Polyurethane Foam Mnaufacture

Sample	Location	Sample Time (Min)	Isocyanates in MAMA Dichotomous Samples ($\mu\text{g}/\text{M}^3$)				Isocyanates in Nitro Reagent Samples ($\mu\text{g}/\text{M}^3$)		
			2,4 TDI	2,6 TDI	MDI	TRIG	2,4 TDI	2,6 TDI	MDI
1	Max Foam	66	20.0	109.4	ND	3.2	13.7	93.4	ND
2	CTM/LFM	278	3.2	11.6	ND	2.9	1.7	10.4	ND
3	Flame Laminate	115	6.3	13.5	ND	2.2	7.8	15.8	ND
4	Zapper	95	0.8	ND	ND	0.4	ND	ND	ND
5	Flame Laminate	5	ND	ND	ND	ND	ND	ND	ND
6	Zapper	114	1.4	14.8	ND	3.6	2.1	16.3	ND
7	CTM/LFM	105	5.1	8.4	ND	3.5	4.1	8.4	ND
8	Max Foam	59	2.1	7.4	ND	4.7	2.4	7.5	ND
*9	Max Foam	67	3.7	29.9	ND	1.5	2.9	160.0	ND
10	Flame Laminate	38	4.5	5.4	ND	ND	8.5	5.3	ND

TRIG: total reactive isocyanate group excluding TDI and MDI. Concentration of TRIG reported in μg NCO.

ND: not detected

* Sample contaminated when edge of foam bat sloughed off and fell onto sampling train.

Table 15 presents the results of the MAMA dichotomous samples broken down by phases: non-respirable aerosol collected by the cyclone inlet, vapor collected by the denuders, and respirable aerosol collected by the backup filter. The majority of isocyanate was found in the vapor phase. Five of the ten samples had measurable amount of isocyanate in the respirable or non-respirable particulate phases. In light of the limited number of samples, no investigations of patterns to the relative amounts of TDI or TRIG in vapor versus aerosol phases for the different areas/processes was attempted. However the data indicated that there might be significant degrees of partitioning between aerosol and vapor phases even for the relatively volatile isocyanates such as TDI. The tendency of the unidentified TRIG compounds present in these samples to partition primarily into the vapor phase added support to the theory that they were lower molecular weight materials as discussed above.

Table 16
Vapor/Aerosol Distribution of Collected Isocyanates / Polyurethane Foam Manufacture

Sample	Phase	2,4 TDI ($\mu\text{g}/\text{M}^3$)	2,6 TDI ($\mu\text{g}/\text{M}^3$)	TRIG ($\mu\text{g}/\text{M}^3$)
1	Vapor	20.0	109.4	3.2
	Respirable Particulate	ND	ND	ND
	Non-Respirable	ND	ND	ND
	Particulate			
2	Vapor	3.2	11.6	2.9
	Respirable Particulate	ND	ND	ND
	Non-Respirable	ND	ND	ND
	Particulate			
3	Vapor	6.3	12.2	2.2
	Respirable Particulate	ND	ND	ND
	Non-Respirable	ND	1.3	ND
	Particulate			
4	Vapor	0.8	ND	0.4
	Respirable Particulate	ND	ND	ND
	Non-Respirable	ND	ND	ND
	Particulate			
6	Vapor	0.7	6.6	3.6
	Respirable Particulate	ND	8.2	ND
	Non-Respirable	0.7	ND	ND
	Particulate			
7	Vapor	3.8	6.9	2.4
	Respirable Particulate	1.3	1.5	ND
	Non-Respirable	ND	ND	1.1
	Particulate			
8	Vapor	1.7	5.0	1.8
	Respirable Particulate	ND	ND	ND
	Non-Respirable	0.4	2.4	2.9
	Particulate			
9	Vapor	3.7	29.9	1.5
	Respirable Particulate	ND	ND	ND
	Non-Respirable	ND	ND	ND
	Particulate			
10	Vapor	4.5	5.4	ND
	Respirable Particulate	ND	ND	ND
	Non-Respirable	ND	ND	ND
	Particulate			

TRIG: total reactive isocyanate group excluding TDI and MDI

ND: not detected

7.) Conclusions

This work has demonstrated that MAMA reagent is superior to either MOPIP reagent or TRYP reagent for measurement of TRIG. While MOPIP is used in the only currently NIOSH-specified technique for measurement of TRIG, the results from this study indicate that the performance of the MOPIP method is likely to suffer when specific standard compounds are not available for use in the analysis. Tryptamine (TRYP) is a newer and more promising reagent for measurement of TRIG. This work suggests that it is superior to MOPIP in providing consistency of response across TRIG forms. However it was found to be more difficult to work

Note: NIOSH Method 5521, which uses MOPIP, was the NIOSH-specified technique for measurement of TRIG until August, 1994. Now, it is limited to monomeric isocyanates only. NIOSH Method 5522, which uses tryptamine, is the current NIOSH method for TRIG determination.

with in terms of the preparation of standard derivative compounds and of the analytical detection techniques used (i.e., electrochemical detection). In addition, the TRYP technique exhibited more overall variability in analytical response across the model isocyanates than did the MAMA technique. The overall consistency of UV absorbance response for the MAMA derivatives of the model isocyanates was remarkably uniform with a RSD of only 8.3% noted for the ratio of UV absorbances at 245 nm and 370 nm for the eleven model isocyanates examined. Further, UV absorbance detection is a well established and simple technique for HPLC analyses, in comparison to either electrochemical detection or fluorescence. In addition the MAMA group is such an intense UV chromophore that little loss in sensitivity of analysis is observed in comparison to the generally higher sensitivities of fluorescence and electrochemical detection. Further, the application of the MAMA technique to a series of commercial oligomeric/pre-polymeric materials containing free isocyanate clearly showed the utility of the method in identifying and quantitating TRIG, even when the exact chemical structure of the isocyanate-containing material is unknown.

An underlying hypothesis of this work was that certain isocyanates would exhibit a tendency to partition between vapor and aerosol/condensed phases as a function of concentration, method of generation, and inherent volatility. The dichotomous sampler developed in this work was able to definitively separate and independently quantitate vapor and aerosol fractions of TRIG in the laboratory and in actual workplaces. The performance of the device was consistent with that predicted from theory and corresponded with independent measures of vapor and aerosol isocyanate. Evidence provided by the dichotomous sampler of partitioning of semi-volatile isocyanates in the laboratory and in the field for the first time clearly illustrated the significance of this phenomenon, and as a result, has generated new questions concerning the behavior of isocyanates in the workplace environment.

Overall, this project has resulted in the development, evaluation and demonstration of a powerful new technique for measurement of TRIG levels in the workplace and its speciation into the vapor and aerosol fractions. The results of this work point out the need for further research into the exact nature of TRIG from industrial processes, particularly those that may generate new isocyanate containing materials as polymerization reactions proceed, and those that may regenerate isocyanate from fully cured polymeric material through high temperature degradation. These questions are amenable to investigation with this newly developed research tool. Further, it should now be feasible for the first time to conduct quantitative assessments of exposure to TRIG in the workplace which could be used in support of epidemiologic investigations designed to assess the risk of occupational disease associated with exposure to the non-traditional forms of isocyanate.

8.) Literature Cited

1. Weyel DA, Ridney BS, Alarie Y. Sensory irritation, pulmonary irritation and acute lethality of a polymeric isocyanate and sensory irritation of 2,6-toluenediisocyanate. *Tox Appl Pharm* 1982; 64:423-430.
2. Belin L, Hjortsberg U, Wass U. Life threatening pulmonary reaction from car paint containing prepolymerized isocyanate. *Scand J Work Environ Health* 1981; 7:310-311.
3. Nielsen J, Sango C, Winroth G, Hallberg T, Skerfving S. Systemic reactions associated with polyisocyanate exposure. *Scand J Work Environ Health* 1985; 11:51-54.

4. Fujimura N, Kino T, Nagtai S, *et al*. Hypersensitivity pneumonitis in a polyurethane paint sprayer. *Nippon Kyobu Shikkan Gakkai Zasshi* 1984; 22:506-513.
5. Jones RN, Rando RJ, Glindmeyer HW, Foster T, Hughes J, O'Neil CE. Abnormal lung function in polyurethane foam producers: weak relationship to measured TDI exposures. Submitted to the American Thoracic Society Annual Meeting, 1991.
6. Rando RJ, Abdel-Kader HM, Hammad YY. Isomeric composition of airborne TDI in the polyurethane foam industry. *Am Ind Hyg Assoc J* 1984; 45:199.
7. Rando RJ, Abdel-Kader H, Hughes JM, Hammad YY. Toluene diisocyanate exposures in the flexible polyurethane foam industry. *Am Ind Hyg Assoc J* 1987; 48:580.
8. White WG, Sugden E, Morris MJ, Zapata E. Isocyanate induced asthma in a car factory. *Lancet* 1980; 1:756-760.
9. Woolley WD. Nitrogen containing products from the thermal decomposition of flexible polyurethane foams. *Br Polym J* 1972; 4:27-43.
10. Renman L, Sango C, Skarping G. Determination of isocyanate and aromatic amine emissions from thermally degraded polyurethanes in foundries. *Am Ind Hyg Assoc J* 1986; 47:621-628.
11. Krzymien ME. Analysis of the effluents from polyurethane foam heated at 80°C. *Am Ind Hyg Assoc J* 1987; 48:67-72.
12. Bagon DA, Warwick CJ, Brown RH. Evaluation of total isocyanate-in-air method using 1-(2-methoxyphenyl)piperazine and HPLC. *Am Ind Hyg Assoc J* 1984; 45:39-43.
13. NIOSH Manual of Analytical Methods, 3rd Edition, Method No. 5505, National Institute for Occupational Safety and Health.
14. Seymour MJ, O'Connor PF, Teass AW. Investigation of the inaccuracy of NIOSH Method 5505 for estimating the concentration of isocyanate in air. *Appl Occup Environ Hyg* 1990; 5:115-122.
15. Teas AW, Seymour MJ. Isocyanate analysis - NIOSH Method 5505. *Appl Ind Hyg* 1987; 2:182.
16. United Kingdom Health and Safety Executive, Research and Laboratory Services Division, London, Method MDHS 25.
17. Ohrin PM, Lingg RD, Line FJ. An evaluation of the effectiveness and accuracy of a total isocyanate method - MDHHS 25. Presented at the American Industrial Hygiene Conference, Orlando, May 15, 1990.
18. Sango C, Zimerson E. A new reagent for determination of isocyanates in working atmospheres by HPLC using UV or fluorescence detection. *J Liq Chrom* 1980; 3:971-990.
19. Lesage J, Perrault G, Desjardins F. Evaluation of isocyanates in work areas. Presented at the American Industrial Hygiene Conference, Montreal, May 31, 1987.
20. Wu WS, Nazar MA, Gaiind VS. Application of tryptamine as a derivatising agent for airborne isocyanates determination. Part 1: Model of derivatisation of methyl isocyanate characterized by fluorescence and amperometric detection in high-performance liquid chromatography. *Analyst* 1987; 112:863-866.
21. Wu WS, Szklar RS, Gaiind VS. Application of tryptamine as a derivatising agent for airborne isocyanate determination. Part 2: Dual function of tryptamine for calibration and derivatisation of poly(methylene [polyphenyl isocyanate]) for quantification by high performance liquid chromatography. *Analyst* 1988; 113:1209-1212.
22. Dharmarajan V, Weill H. Physical state of airborne p,p' diphenylmethane diisocyanate and its measurement. *Am Ind Hyg Assoc J* 1978; 39:737.
23. Dharmarajan V. Occupational exposures to methylene bisphenylisocyanate: gaseous or aerosol? *J Env Path Toxic* 1979; 2:1.

24. Rosenberg C, Pfaffli P. A comparison of methods for the determination of diphenylmethane diisocyanate (MDI) in air samples. *Am Ind Hyg Assoc J* 1982; 43:160.
25. Andersson K, Gudehn A, Levin J, Nilsson CA. A comparative study of solvent and solvent-free sampling methods for airborne 4,4'-diphenylmethane diisocyanate (MDI) generated in polyurethane production. *Am Ind Hyg Assoc J* 1983; 44:802.
26. Brochhagen FK, Schal HP. Diphenylmethane diisocyanate: the concentration of its saturated vapor. *Am Ind Hyg Assoc J* 1986; 47:225.
27. "Criteria for a Recommended Standard: Occupational Exposure to Diisocyanates." NIOSH Publication No. 78-215, 1978.
28. Rando RJ, Hammad YY. A laboratory evaluation of the kinetics of the decomposition of toluene diisocyanate in humid air. Presented at the American Industrial Hygiene Conference, Orlando, May, 1990.
29. Holdren MW, Spicer CW, Riggan RM. Gas phase reaction of toluenediisocyanate with water vapor. *Am Ind Hyg Assoc J* 1984; 45:626.
30. NIOSH Manual of Analytical Methods, 2nd Edition, Volume 1, No. P&CAM 142.
31. Drinker P, Hatch T. *Industrial Dust*. 2nd Edition. New York: McGraw Book Company, 1954.
32. Fish BR, Durham LJ. Diffusion coefficient for sulfur dioxide in air. *Envir Lett* 1971; 2:13.
33. Gormley PG, Kennedy M. Diffusion from a stream flowing through a cylindrical tube. *Proc Roy Ir Acad* 1949; 52:163.
34. Passanzini M, Febo A, Liberti A. New design of a high-performance denuder for the sampling of atmospheric pollutants. *Atmos Environ* 1983; 17:2605-2610.
35. Possanzini M, Febo A, Cecchini F. Development of a KI annular denuder for NO₂ collection. *Anal Lett* 1984; 17:887-886.
36. Febo A, DiPalo V, Possanzini M. The determination of tetraalkyl lead in air by a denuder diffusion technique. *Sci Total Environ* 1986; 48:187-194.
37. Cecchini F, Febo A, Possanzini M. High efficiency annular denuder for formaldehyde monitoring. *Anal Lett* 1985; 18:681-683.
38. Koutrakis P, Wolfson JM, Slater JL, *et al.* Evaluation of an annular denuder/filter pack system to collect acidic aerosols and gases. *Environ Sci Technol* 1988; 22:1463-1468.
39. Brauer M, Koutrakis P, Spengler JD. Personal exposures to acidic aerosols and gases. *Environ Sci Technol* 1989; 23:1408-1412.
40. Dasch JM, Cadle SH, Kennedy KG, Mulawa PA. Comparison of annular denuders and filter packs for atmospheric sampling. *Atmos Environ* 1989; 23:2775-2782.
41. Koutrakis P, Wolfson JM, Spengler JD. An improved method for measuring aerosol strong acidity: results from a nine-month study in St. Louis, Missouri, and Kingston, Tennessee. *Atmos Environ* 1988; 22:157-162.
42. Dimmock NA, Marshall GB. The determination of free ammonia in ambient air with diffusion/denuder tubes. *Analyt Chemica Acta* 1986; 185:159-169.
43. Brauer M, Koutrakis P, Wolfson JM, Spengler JD. Evaluation of the gas collection of an annular denuder system under simulated atmospheric conditions. *Atmos Environ* 1989; 23:1981-1989.
44. Vossler TL, Stevens RK, Paur RJ, Baumgardner RE, Bell JP. Evaluation of improved inlets and annular denuder systems to measure inorganic air pollutants. *Atmos Environ* 1988; 22:1729-1736.

45. Koutrakis P, Fasano AM, Slater JL, Spengler JD, McCarthy JF, Leaderer BP. Design of a personal annular denuder sampler to measure atmospheric aerosols and gases. *Atmos Environ* 1989; 23:2767-2773.
46. David DJ, Stoley HB. Analytical Chemistry of the Polyurethanes. (Wiley Interscience: New York) 1969, pp.87-90.
47. NIOSH Manual of Analytical Methods, 2ND Edition, Volume 7, Method P&CAM 347: 4,4'-methylene-bis-(phenylisocyanate) [MDI]. (NIOSH: Cincinnati).
48. Hammad YY, Rando RJ, Abdel-Kader H. Considerations in the design and use of human inhalation challenge delivery systems. *Fol Allerg Immunol Clin* 1985; 32:37.
49. Rando RJ, Hammad YY. Preparation of diisocyanate atmospheres for use in inhalation challenge testing. Paper presented at the American Industrial Hygiene Conference, San Francisco, May, 1988.
50. Tucker WA, Nelken LH. Diffusion coefficients in air and water. In: Lyman WJ, Reehl WF, Rosenblatt DH (eds), *Handbook of Chemical Property Estimation Methods*. New York: McGraw-Hill, 1982.
51. Dharmarajan V, Rando RJ. A new method for the generation of standard atmospheres of organo-isocyanates. *Am Ind Hyg Assoc J* 1979; 40:870.

9.) Publications Supported by this Grant

1. Rando RJ, Poovey HG, Lefante JJ, Esmundo FR: Evaluation of 9-methylamino-methylanthracene as a chemical label for total reactive isocyanate group: a comparison of mono- and di-isocyanate monomers. *J Liquid Chrom* 1993; 16:3977-3996.
2. Rando RJ, Poovey HG: Dichotomous sampling of vapor and aerosol of methylene-bis-(phenylisocyanate) [MDI] with an annular diffusional denuder. *Amer Ind Hyg Assoc J* 1994; 55:716-721.
3. Rando RJ, Poovey HG, Gibson RA: Evaluation of 9-methylamino-methylanthracene as a chemical label for total reactive isocyanate group: application to isocyanate oligomers, polyurethane precursors, and phosgene. *in press, J Liquid Chromatography* 1995.

10.) Publications Planned for the Future

1. Rando RJ, Poovey HG: Characterization of HDI, HDI-Biuret and total reactive isocyanate group (TRIG) in polyurethane paint overspray environments.
2. Rando RJ, Poovey HG: Characterization of total reactive isocyanate group (TRIG) in the flexible polyurethane foam manufacturing environment.
3. Rando RJ, Poovey HG, Gibson RA: Measurement of aerosol/vapor phase partitioning of HDI, HDI-biuret and total reactive isocyanate group (TRIG) with a denuder-based dichotomous sampler.

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